ERRATA

Page v    Read  Table 2-B...p. 92 for Table 2-B...p. 96

Page v    Read  Table 4.....p. 98 for Table 4.....p. 97

Page 128    Read  mph/summer season for mph

Page 142    Read

$$b = \frac{\sum XY - \frac{(\sum X)(\sum Y)}{n}}{\sum X^2 - \frac{(\sum X)^2}{n}} \quad \underline{\text{for}} \quad b = \frac{\epsilon xy - \frac{(\epsilon x)(\epsilon y)}{n}}{\epsilon x^2 - \frac{(\epsilon x)^2}{n}}$$

Read $$a = \frac{\sum Y}{n} - b\frac{\sum X}{n} \quad \underline{\text{for}} \quad a = \frac{\epsilon y}{n} - b\frac{\epsilon x}{n}$$

Page 147    Read  p. 123 for p. 122.

# POSTGLACIAL UPLIFT IN THE GREAT LAKES REGION

by

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Special Report No. 14
Great Lakes Research Division
Institute of Science and Technology

The University of Michigan
Ann Arbor, Michigan
December 1961

## PREFACE

The purpose of this study is to analyze and evaluate the factors involved in the determination of modern rates of postglacial crustal movement in the Great Lakes region in order to ascertain the validity of previously determined rates of uplift.

Because the calculation of uplift rates are based on findings from many fields, i.e., geology, geophysics, geodesy, meteorology, oceanography, and engineering, it is necessary to integrate information from all of these fields if a solution to the problem is to be found.

Data and aid from the following organizations and individuals are gratefully acknowledged: U. S. Lake Survey (lake-level elevations, gage histories, operating procedures); Canadian Hydrographic Service (precise leveling and gage histories, lake-level elevations); Canadian Meteorological Division (wind, temperature, and barometric pressure data); Great Lakes Research Division, Institute of Science and Technology, The University of Michigan (financial support, July, 1960, through January, 1961, and reproduction of report); University of Michigan Computing Center (computer time for r correlations); Professor L. I. Briggs and Frank Moser (correlation computer program); U. S. National Weather Records Center (wind data); and the members of my doctoral committee, Professors J. T. Wilson, J. C. Ayers, L. I. Briggs, D. F. Eschman, and J. H. Zumberge.

The text of this report was submitted as a doctoral dissertation to the Horace H. Rackham School of Graduate Studies, The University of Michigan.

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ABSTRACT

The purpose of this study is to analyze and evaluate the factors which are involved in the determination of modern rates of postglacial crustal movement in the Great Lakes region in order to ascertain the validity of previously determined rates of uplift.

Because the calculations of rates of uplift are based on findings from many fields, i.e., geology, geophysics, geodesy, meteorology, oceanography, and engineering, it is necessary to integrate information from all of these fields if a solution to the problem is to be found.

The problem was studied by the following methods:
(a) by analyzing the data, methods, and results of previous investigators of modern uplift; (b) by comparing modern areas and rates of uplift with areas and rates of uplift based on differential warping of former glacial lake shoreline features; (c) by comparing modern uplift in the Great Lakes region with modern uplift in Fennoscandia; (d) by examining principles of operation, instrument construction, external influences, and errors which are inherent in water-level gaging (the results of gaging are used to calculate modern rates of uplift); (e) by computing daily, monthly and summer season vector winds for Lakes Erie, Ontario and Superior (1950-59) in order to test the assumption (underlying water-leveling and the calculation of rates of uplift) that the summer mean Great Lakes water surfaces are level; and (f) by making a correlation study of effective wind velocities and lake-level gage differences to determine if gage differences represent land uplift, or wind slope of the lake surface.

The results indicate that: (a) all previously determined modern rates of uplift on Lake Erie are not valid because Lake Erie is in the postglacial area of horizontality; (b) all rates of modern uplift based on pairs of gages in which one gage is south of the Nipissing zero isobase are also not valid; and (c) rates of uplift on Lake Superior and on the other Great Lakes which are based on records of gage pairs located north of the Nipissing zero isobase are probably erroneous owing to the inclusion in the gage differences of errors caused by meteorological effects, gage location effects, instrument error and operator error.

Six of the more important conclusions are:
1. Lake-level gages used to detect and measure modern uplift must be north of the known area of horizontality (i.e., north of the Nipissing zero isobase). Gage records must be corrected for meteorological, in-

strument and operator errors.

2. The Lake Erie correlation study showed that gage differences represent, almost wholly, meteorological effects and not uplift.

3. The summer season mean water surfaces of the Great Lakes are not level.

4. Ekman's theory of ocean currents should be re-examined and modified on the basis of empirical observations.

5. The Lake Erie correlation study indicated that Ekman's concept of water-surface slope direction being in the direction of the wind is incorrect; on Lake Erie the water-surface slope direction is about 23° to the right of the wind.

6. The angle of deviation of surface currents from wind directions on Lake Erie (c 23° to the right) should also be representative of the angle of deviation for the other Great Lakes.

# I. HISTORICAL INTRODUCTION

## Fennoscandia

The phenomenon of land rising from a body of water has been a subject of study and speculation since Classical times. Although Greek, Roman and Medieval writers recorded the uplift of land in volcanic areas, it was not until 1625 that slow imperceptible uplift of land in a non-volcanic region was mentioned in a Finnish book of discourses.

The gradual seaward retreat of the shorelines of the shallow Baltic Sea and the Gulf of Bothnia, as well as the shoaling of harbors and waterways, caused Scandinavian naturalists of the late 17th and early 18th centuries to speculate as to its cause. The question soon arose as to whether the land in the Baltic area was rising, or the quantity of water in the sea diminishing. Such noted scientists as Linnaeus, Celsius and Swedenborg held that the waters of the Baltic Sea were decreasing.

In an effort to actually measure the change between land and sea, Anders Celsius made what is probably the first systematic observations of this relative change when, in 1731, he had marks corresponding to sea level and the date chiseled into exposed bedrock. By comparing later marks with the 1731 mark, Celsius estimated the lowering of sea level to be 4.1 feet per century. (Kääriäinen, 1953, p. 7).

The theory of diminishing water was shown to be false by the Bishop of Abo, Johan Browallius, in 1755 when he pointed out that the sea maintains an equilibrium and that churches built in Sweden in the 13th century were still near the shore and ancient buildings in southern Sweden and Denmark were still on the shore; therefore a general decrease of sea level could not have occurred. (Kääriäinen, 1953, p. 8; Thorarinsson, 1940, p. 132; Bergsten, 1930, p. 21).

E. O. Runeberg of Finland was the first proponent of crustal elevation as the cause of the shifting of the coastline of the Gulf of Bothnia. His observations and studies led him to declare in 1765 that the earth's crust rises while sea level remains the same. (Kääriäinen, 1953, p. 8; Bergsten, 1930, p. 21.) This view was also supported by Playfair (1802, pp. 445-447) in his Illustrations of the Huttonian Theory and by Von Buch (1813, p. 386) in his Travels through Norway and Lapland during the years 1806, 1807 and 1808.

Charles Lyell (1837, pp. 437-449) discussed the uplift of land in the Baltic region in "Chapter XVII, Elevation and Subsidence of Land without Earthquakes" in his Principles of Geology. This chapter, which summarized the investigations and observations which had been made before 1837, concluded with remarks as to the significance of a slow secular uplift and speculated as to its cause. Lyell's last paragraph of Chapter XVII supplies the views of the possible causes of the Baltic uplift which were current in the first half of the 19th century. He states (1837, p. 449):

> The foundations of the country, thus gradually uplifted in Sweden, must be undergoing important modifications. Whether we ascribe these to an expansion of solid matter by continually increasing heat, or to the liquefaction of rock, or to the crystallization of a dense fluid, or the accumulation of pent-up gases, in whatever conjecture we indulge, we can never doubt for a moment, that at some unknown depth the structure of the globe is in our own times becoming changed from day to day, throughout a space probably more than a thousand miles in length and several hundred in breadth.

The modern theory of the cause of crustal movement in Fennoscandia and North America, i.e., ice unloading and subsequent isostatic adjustment, was proposed by a Scot, Thomas F. Jamieson, in 1865. His theory, quoted in the following paragraph, was later developed in detail in the paper "On the Cause of the Depression and Re-elevation of the Land during the Glacial Period" published in The Geological Magazine in 1882.

Jamieson (1865, p. 178) stated in his first expression of the theory that:

> It is worthy of remark that in Scandinavia and North America, as well as in Scotland, we have evidence of the great ice-covering; and singular to say, the height to which marine fossils have been found in all three countries is very nearly the same. It has occurred to me that the enormous weight of the ice thrown upon the land may have had something to do with this depression. Agassiz considers the ice to have been a mile thick in some parts of America; and everything points to a great thickness in Scandinavia and North Britain. We don't know what is the state of the matter on which the solid crust of the earth reposes. If it is in a state of fusion, a depression might take place from a cause of this kind, and then the melting of the ice would account for the rising of the land, which seems to have followed upon the decrease of the glaciers.

Fennoscandia continued to provide material for research on differential uplift of the land until, according to E. Kääriäinen (1953, p. 9),

fifty or more scientists had investigated uplift in this region before the beginning of the twentieth century. Since 1900 more than forty European and British geologists, geodesists and engineers have studied and reported upon post-glacial and contemporary differential land uplift in the Baltic region.

The importance of Fennoscandian investigations of this secular uplift to similar studies in the Great Lakes area may be briefly stated—the Fennoscandian studies pioneered in the use of water gaging and precise leveling to reveal uplift, in applying corrections (chiefly meteorological) to water gaging in order to reduce systematic errors and in supplying the necessary mechanism for the cause of the uplift.

These European studies, published over a period of more than 200 years, were probably the source of American ideas on this subject. Furthermore, the current Scandinavian literature dealing with modern crustal deformation reveals many concepts and techniques, particularly in the application of corrections for systematic errors, which have not been used in American studies of the same topic.

## Great Lakes Region

Detection of crustal movements in the Great Lakes region has been hampered by the large area involved, by the sparse population (consequently by the limited number of observers), and by the relatively short time that the region has been settled. The limited distribution of obser-

vation points coupled with the short period of recorded observation may help to explain why the first systematic study of "modern" land uplift was not undertaken until 1896 by Dr. G. K. Gilbert.

Three members of the early geological surveys of New York, Ohio and Michigan reported ancient uplifted beaches. Ebenezer Emmons (1837, p. 123), geologist for the New York Natural History Survey, described concurrent land uplift along the St. Lawrence River; he compared it to the uplift in Norway and said that the only way of discovering its magnitude was to establish fixed land marks which would be compared over a number of years. Emmons (1838, p. 239) also discussed uplift in the Lake Champlain area. Charles Whittlesey (1838, p. 55), topographer of the Ohio Geological Survey, reported measuring ancient tilted beaches south of the Lake Erie shore in 1838, and Bela Hubbard (1840, pp. 105-106) of the Michigan Geological Survey described the formation of raised beaches near Lake Erie as follows:

> ...In other words, the land has been subsequently subjected to an upheaving force, which at last has elevated the whole far above the influence of the sea.
>
> Whether the upheaving of the land was general at this era, throughout the continent or was mainly operative in the region of the lakes, probably cannot be satisfactorily determined. It may be competent, however, to suppose that these apparent "lake ridges" were the boundaries of the ancient sea formed during intervals of rest in the upward tendency of the land.
>
> ..............................................................
>
> There also exist strong reasons for supposing that the relative levels of the land did not everywhere remain the same, or that disproportionate elevations took place....

Despite the early recognition of tilted beaches in the lower Great Lakes region it was not until the latter part of the 19th century that the studies of deformed postglacial shoreline features by Bell, Gilbert, Goldthwait, Lawson, Leverett, Spencer, Taylor and Upham provided the proper "atmosphere" for the consideration of modern uplift.

G. R. Stuntz, a Wisconsin surveyor, submitted a paper to the American Association for the Advancement of Science in 1854 in which he suggested that the waters of Lake Superior appeared to be rising at the west end of the lake and falling at the eastern end. This paper, which was published in 1869, was one of the first to infer that a change was taking place in modern times in the relative positions of the lake water and the land (1869, pp. 205-210).

In 1868 (p. 129), N. S. Shaler, while discussing changes of level of shorelines said: "...Looking still further, we perceive some very peculiar features in the distribution of the changes of level which are still going forward, or which have taken place since the close of the glacial period."

The next suggestion that modern land uplift could be occurring was made by Robert Bell in his description of his explorations of the Hudson Bay area. Despite the fact that Bell later (1897) spoke of the "Rising of the Land around Hudson Bay," in his earlier reports he was not as definite in asserting that uplift was occurring. Bell's report published in 1880 spoke of:

> ...the comparatively rapid elevation of the land, or retiring of the sea, around James Bay and at York Factory was referred to in my reports for 1877 and 1878. ... This recession of the sea may be due to a general lowering of its level relatively to the land, and partly to the silting up of portions of Hudson's Bay, interrupting the free flow of the tides (p. 21c).

The first definite statement regarding modern crustal movement in the Great Lakes area was made by J. W. Spencer (1894) in a paper "The Duration of Niagara Falls." He (p. 472) concluded his paper by declaring: "...Lastly, if the rate of terrestrial deformation continues as it appears to have done, then in about 5000 years the life of Niagara Falls will cease by the turning of the waters into the Mississippi." Spencer (1907, 1913) later recanted this hypothesis (the same idea has been expressed by other writers several times since his original utterance) after reworking Gilbert's data in conjunction with additional information.

Grove Karl Gilbert (1896-97) made the first determination of land uplift in the Great Lakes region using "modern" observations. The underlying principles of his procedures and techniques have been followed by all subsequent investigators. Gilbert's original determination of the amount of earth tilting was prompted by the speculation that the forces which had tilted former beaches were still active and could be detected. He made use of the U. S. Lake Survey assumption that a lake surface is level if measured over a "protracted" period to provide the necessary level for comparison between pairs of gages located in the general direction of tilt.

Four pairs of water-level gages were used and the rate of tilting was found by comparing the gage differences for each pair of gages for 1874 with the gage differences of the same pairs for 1896. Because the gage differences were compared in relation to the same datum (the level lake surface) they would have been the same in 1896 as in 1874 if no tilting had occurred. However, the gage differences for 1896 differed from those of 1874 which caused Gilbert to conclude that tilting had occurred during the intervening years.

Gilbert's awareness of the pitfalls which were present in his assumptions, raw data, and method of calculation induced him to include a discussion of the sources and importance of errors inherent in the data and method. His report also included a section on "Plans for Precise Measurement," which, if followed, would have greatly reduced or eliminated the systematic errors which are still intrinsic in water-level records.

The next two studies of modern crustal movement were made by J. W. Spencer in 1907 and 1913. Spencer applied Gilbert's techniques to the study of gage records taken from 1855 to 1905 in the first paper and from 1855 to 1912 in the second paper. He calculated the gage differences for periods of five years (using the mean daily lake levels), and concluded from his study that the means of all the five year periods from 1855 to 1912 were within the limits of the probable error—therefore the earth's crust was stable.

These investigations were followed by a paper in 1922 by Sherman Moore, an engineer of the U. S. Lake Survey. Again using the procedure originated by Gilbert, Moore examined 18 pairs of gages whose periods of record were from 1870-80 to 1919. The gages were located on all of the Great Lakes, including Lake Superior. Moore's determination of the rates of uplift for Lake Superior were the first calculated for that lake. His conclusion was that tilting of the land occurs on all of the lakes but that the rates vary for different lake basins. Moore's estimate of the general rate of tilting was about six inches in one hundred miles in one hundred years.

The controversy arising from the diversion of water from Lake Michigan by the City of Chicago led to two studies of the hydrology of the Great Lakes. These studies, one by John R. Freeman in 1926 and the other by R. E. Horton and C. E. Grunsky in 1927, included determinations of land uplift. Both papers reviewed the literature dealing with this topic and both recalculated the rate of movement. The results were essentially the same as had been found by previous investigators, although Horton and Grunsky concluded that no uplift was occurring around Lake Erie.

Beno Gutenberg (1933) conducted an investigation of "Tilting Due to Glacial Melting," including not only the Great Lakes region but also Hudson Bay and Scandinavia. His paper included a compilation of previous work on crustal deformation, the calculation of rates of movement on

the Great Lakes from 28 pairs of gages, and a discussion of the determination of changes of level by means of the examination of ocean tide gage records. His results concurred with those of Gilbert, Moore and Freeman.

Eight years after his first paper on postglacial tilting, B. Gutenberg (1941) published a much more comprehensive work "Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior." Using additional lake-level gages and tide gages, Gutenberg made new calculations of the rates of uplift in both North American and Fennoscandia, which he demonstrated could be used to help determine the viscosity and strength of the earth.

Sherman Moore's (1948) second paper on "Crustal Movement in the Great Lakes Area" was the result of data which had been accumulated in order to establish a new datum (1935 Datum) on the Great Lakes.

The re-leveling, both water and instrumental, which was necessary to establish the new datum permitted Moore to determine the rates of uplift in relation to sea level. Moore's analysis of the data led to a number of interesting conclusions, several of which do not concur with current geologic thought. Moore (p. 697) inferred that, "The entire area, except for the extreme northerly part of Lake Superior is subsiding with respect to sea level." He (p. 708) also stated, "Whatever the cause of the postglacial warping, there seems to be no connection between the present movement and isostatic recovery from the weight of the ice."

In 1954 Charles A. Price of the Canadian Hydrographic Service reported on the "Crustal Movement in the Lake Ontario—Upper St. Lawrence River Basin." The procedures which he used were those employed by previous investigators. Price (1954, Pl. 0-6) reported the over-all change in gage relations as 0.53 feet per 100 miles per 100 years with tilting occurring in a direction N 40° E.

The most recent determination of rates of crustal movement in the Great Lakes region are those of the Vertical Control Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. The Subcommittee, which is composed of Canadian and American members, was appointed to establish a new level datum for the Great Lakes. Part of its duties included the study of crustal movements. The results of the Subcommittee findings have not been published although interim reports have been issued to participating government agencies.

The techniques which are used by the Subcommittee to calculate rates of movement are those which were originated by Gilbert in 1896. Although certain minor specifications were made as to the data to be used, the Subcommittee has not analyzed the concepts or assumptions which are inherent in the calculation of rates of movement by the lake-level gage procedure; therefore it may be expected that its findings will agree for the most part with prior determinations.

## II. LAND UPLIFT

"Land uplift" which is defined as, "Elevation of any extensive part of the earth's surface relatively to some other part...." (A.G.I., 1951, p. 310) will be restricted in this study to the differential vertical movement of land in the former glaciated areas of Fennoscandia and North America.

The existence of this land uplift has been revealed by the measurement of warped former shoreline features of late and postglacial water bodies; by examination of water-level gage records of modern lakes and seas; and by precise leveling.

As the ice sheets of Late Wisconsin time retreated in the Great Lakes region toward the center of glaciation in the area of Hudson Bay, large lakes were formed by glacier ice blocking the normal drainage of the land. The waters of these glacier-margin lakes rose until they were able to escape to the south over low areas of the Great Lakes watershed. As the glacier front retreated, or occasionally advanced slightly, various outlets were covered or uncovered, which allowed the lakes to vary in size and elevation. The lake levels remained constant long enough for shoreline features, i.e., beaches, wave-cut cliffs, deltas, to be developed on the emerging shores. Shoreline features which were level when first built are now found to be warped upward toward the northeast

in the northern part of the lake basins. The greatest tilt is measured in the highest (oldest) shorelines.

This progressive northward warping of the shorelines is due to a differential uplift of the earth's crust which most geologists believe to be caused by recovery of the crust after depression by the load of the glacial ice.

The tendency of portions of the earth's crust to approach a condition of balance leads to the establishment of a state of equilibrium in the crust known as "isostasy." The upwarping of strandlines in former glaciated areas has been cited by many geologists and geophysicists as one of the most convincing proofs of the principle of isostasy.

## Mechanics of Warping

The determination of the underlying cause of warped shoreline features in Fennoscandia and North America has unfortunately been complicated by the fact that the glaciated areas correspond very closely with the Baltic Shield and the Canadian Shield, regions where the movements have been upward for a long period of time (see Plate I).

Scientists who explain the upwarping by isostatic rebound are opposed by those who believe that modern uplift is a continuation of movements which have characterized shield areas since Precambrian times. One of the adherents of the tectonic, endogenetic theory of land uplift in these areas summarized this concept by stating:

> That both the Canadian and the Baltic shields were being elevated, clearly by tectonic forces, prior to the glacial period; and there are no grounds for maintaining that the very same forces did not play an important role in the recent movement of the shields (Lyustikh, 1960, p. 107).

The arguments of the proponents for a tectonic cause of uplift were answered, for the most part, by R. A. Daly (1940, p. 318) who declared:

> This hypothesis, that there is no connection between the upwarping and the deglaciation shows its full weakness when confronted with field statistics. We might conceive that the observed systematic warping in one or two tracts might be explained by independent epeirogenic movements, but it seems incredible that in a dozen regions the same type of warping should appear as mere accidental products of a stress system that has no vital connection with ice-loads. Yet basining and recoil have been demonstrated in as many widely separated tracts, each having been covered with heavy masses of ice recently melted away. In some, if not all, of the cases the melting and warping began less than 50,000 years ago. With few exceptions there are no signs that the lithosphere outside these tracts was simultaneously disturbed by anything like the same amount.

## Isostasy

The first clear explanation of the theory of isostasy came out of an attempt to explain certain systematic errors in the calculations of the Trigonometrical Survey of India in the first half of the nineteenth century. When latitudes and longitudes derived from astronomical observations were compared with latitudes and longitudes of the same stations computed from the triangulation net, it was found that the relative position determined by triangulation failed to agree with the astronomical positions by an amount which could not be accounted for by surveying error.

Insert - Plate I: Features of Postglacial Land Uplift, Great Lakes-Hudson Bay Region
20-½" x 26-¼"

The determinations of astronomic positions are made with instruments containing leveling bubbles; therefore the vertical axis of the instrument is perpendicular to the geoid; i.e., the vertical axis, like a plumb line, is parallel to the direction of the force of gravity. On the other hand, triangulation positions are calculated on the basis of an assumed ellipsoid and yield geodetic latitudes and longitudes; perpendiculars to these coordinates are normal to the ellipsoid. The angle between the normal to the ellipsoid and the normal to the geoid is called "the deflection of the vertical."

It has long been known that a plumb line (normal to the geoid) is attracted by the mass of a mountain (Newton, 1728, p. 41) and that the magnitude of attraction is less than would be expected if the attractive force depended solely upon the mountain's mass as computed by its dimensions and the average density of rock (Bouguer, 1749, pp. 364-385; Maskelyne, 1775, pp. 500-508; DeZach, 1814, pp. V-XVI). However, it was not until 1855 when two papers dealing with this subject were published in the <u>Philosophical Transactions of the Royal Society of London</u> that an explanation for this phenomenon was advanced.

John H. Pratt, an archdeacon of Calcutta, discussed the systematic error which had been revealed in a comparison of the astronomic and geodetic determinations of latitude of the terminal points of the northern division of the Meridional Arc of India. After proving that the geodetic calculations were not at fault, Pratt pointed out that the plumb line of

the astronomical observations must have been affected by the mass of the Himalayas and the Tibetan plateau. He computed the magnitude of the attraction by means of a laborious mechanical integration of the topographic effect of the mass of the Himalayas and the mountain region beyond. His computations showed that the difference between the calculated deflections of the plumb line at Kalianpur on the central plateau and Kaliana at the foot of the Himalayas was three times larger than the measured deflection.

Although Pratt (1855, p. 100) declared, "The conclusion, then, to which I come is, that there is no way of reconciling the difference between the error in latitude deduced in Colonel Everest's work and the amount I have assigned to deflection of the plumb line arising from attraction. ...;" the next paper in the same volume of the Transactions provided the answer to the problem.

George B. Airy, Astronomer Royal of Great Britain, heard the original presentation of Rev. Pratt's paper on December 7, 1854, and, in 1855, submitted a short paper to the Royal Society which expressed for the first time the principles of that condition of equilibrium in the earth's crust which was later called "isostasy." In his succinct paper Airy explained that the fluidity of the earth's interior was imperfect; that it was probably extremely viscous; that the material below the crust was of greater density than the crust; and that the strength of the crust was insufficient to support the weight of a table-land or to maintain a mountain range, although it would support local topographic features such as

a mountain. He (1855, p. 163) expressed his views of the underlying support for elevated regions of the earth's crust as follows:

> I conceive that there can be no other support than that arising from the downward projection of a portion of the earth's light crust into the dense lava; ... the depth of its projection downwards being such that the increased power of floatation thus gained is roughly equal to the increase of weight above from the prominence of the table-land. ...

In regard to the effect on gravity of the elevated portion of the crust and its downward projection, Airy (1855, pp. 103-104) said:

> Let us consider what will be its effect in disturbing the direction of gravity at different points in its proximity. It will be remarked that the disturbance depends on two actions; the positive attraction produced by the elevated table-land; and the diminution of attraction, or negative attraction, produced by the substitution of a certain amount of light crust (in the lower projection) for heavy lava.
>
> The diminution of attractive matter below, produced by the substitution of light crust for heavy lava, will be sensibly equal to the increase of attractive matter above. The difference of the negative attraction of one and the positive attraction of the other, as estimated in the direction of a line perpendicular to that joining the centers of attraction of the two masses (or as estimated in a horizontal line), will be proportional to the difference of the inverse cubes of the distances of the attracted point from the two masses. ...
>
> ............................................................
>
> The general conclusion then is this. In all cases, the real disturbance will be less than that found by computing the effects of the mountains, on the law of gravitation. Near to the elevated country, the part which is to be subtracted from the computed effect is a small proportion of the whole. At a distance from the elevated country, the part which is to be subtracted is so nearly equal to the whole, that the remainder may be neglected as insignificant, even in cases where the attraction of the elevated country itself would be considerable. But in our ignorance of the depth at which the downward immersion of the projecting crust into the lava takes place, we cannot give greater precision to the statement.

Airy recognized that isostasy may be incomplete—this is revealed in his statement (1855, p. 104) that:

> In all the latter inferences, it is supposed that the crust is floating in a state of equilibrium. But in our entire ignorance of the modus operandi of the forces which have raised submarine strata to the tops of high mountains, we cannot insist on this as absolutely true. We know (from the reasoning above) that it will be so to the limits of breakage [strength of the crust] of the table-lands; but within those limits there may be some range of the conditions either way. It is quite possible that the immersion of the lower projection in the lava may be too great, as that the elevation may be too great; and in the former of these cases, the attraction would be negative.

Four years after Airy made public his theory of the equilibrium of the earth's crust, J. H. Pratt (1859) published a second paper on the deflection of the plumb line in India which supplies the rudiments for the hypothesis known as "Pratt's Theory of Isostasy."

Although Pratt admitted in the beginning of his paper that Airy's concept of a deficiency of mass beneath the mountain mass was correct, he rejected Airy's explanation of the phenomenon and proposed one of his own. Pratt (1859, pp. 746-747) states his objection to Airy's theory as follows:

> This hypothesis appears, however, to be untenable for three reasons: (1) It supposes the thickness of the earth's solid crust to be considerably smaller than that assigned by the only satisfactory physical calculation made on the subject—those by Mr. Hopkins of Cambridge. He [Mr. Hopkins] considers the thickness to be about 800 or 1000 miles at least. (2) It assumes that this thin crust is lighter than the fluid on which it is suppose to rest. But we should expect that in becoming solid from the fluid state, it would contract from loss of heat and become heavier. (3) The same reasoning by which Mr. Airy makes it appear that every pro-

> tuberance outside this thin crust must be accompanied by a protuberance inside, down into the fluid mass, would equally prove that wherever there was a hollow, as in deep seas, in the outer surface, there must be one also in the inner surface of the crust corresponding to it; thus leading to a law of varying thickness which no process of cooling would have produced.

Pratt (1859, p. 751) explained the deficiency of matter beneath the mountain mass in the following way:

> ... At the time when the earth had just ceased to be wholly fluid, the form must have been a perfect spheroid, with no mountains and valleys nor mountain hollows. As the crust formed, and grew continually thicker, contractions and expansions may have taken place in any of its parts, so as to depress and elevate the corresponding portions of the surface. If these changes took place chiefly in a vertical direction, then at any epoch a vertical line drawn down to a sufficient depth from any place in the surface will pass through a mass of matter which has remained the same in amount all through the changes. By the process of [thermal] expansion the mountains have been forced up, and the mass thus raised above the level has produced a corresponding attenuation of matter below. This attenuation is most likely very trifling, as it probably exists through a great depth. ...

The deflection of the plumb line caused by the mass of the Himalayas and the mountain region beyond was calculated by Pratt as 27.978 sec at Kaliana (at the foot of the Himalayas) and the difference of the deflection of the plumb lines at Kaliana and Kalianpur as 15.931 sec. He then computed the deflection as modified by the supposed attenuation below the mountains assuming that the level of attenuation extended down to a depth of 100, 300, 500 and 1000 miles. His figures showed that the deflection at Kaliana, if the attenuation were extended down to the 100 mile level would be 1.538 sec and the difference between Kaliana and Kalianpur would

be 1.602 sec. However, the measured difference of deflection at Kaliana and Kalianpur was 5.236 sec which would require a depth of attenuation of almost 300 miles. The problems posed by these results led Pratt (1859, p. 762) to declare, "... No hypothesis of deficiency of matter below, which we can conceive will remove the anomaly. The disturbing cause must be elsewhere; ..."

Despite the fact that all of Pratt's concepts of the nature of the earth's crust (except that rock densities vary horizontally) have been disproved, his theory of isostasy (in greatly modified form) is still being used to reduce gravity anomalies and, indirectly, to compute the size and shape of the earth.

The concepts contained in the hypotheses of Airy and Pratt are the basis for several isostatic systems in use at the present time; the principal ones being the Pratt-Hayford system, the Airy-Heiskanen system and the Vening Meinesz system.

Figure 1 presents a schematic representation of the structure of the earth's crust based on the concepts of: (a) Airy, (b) Pratt (modified), and (c) a composite view—probably the closest approach to actual conditions in the crust.

## ISOSTATIC RECOVERY

### Glacial Loading

The Hudson Bay-Great Lakes area was covered by a continental glacier of Wisconsin age which was probably more than 3,000 meters (10,000 ft)

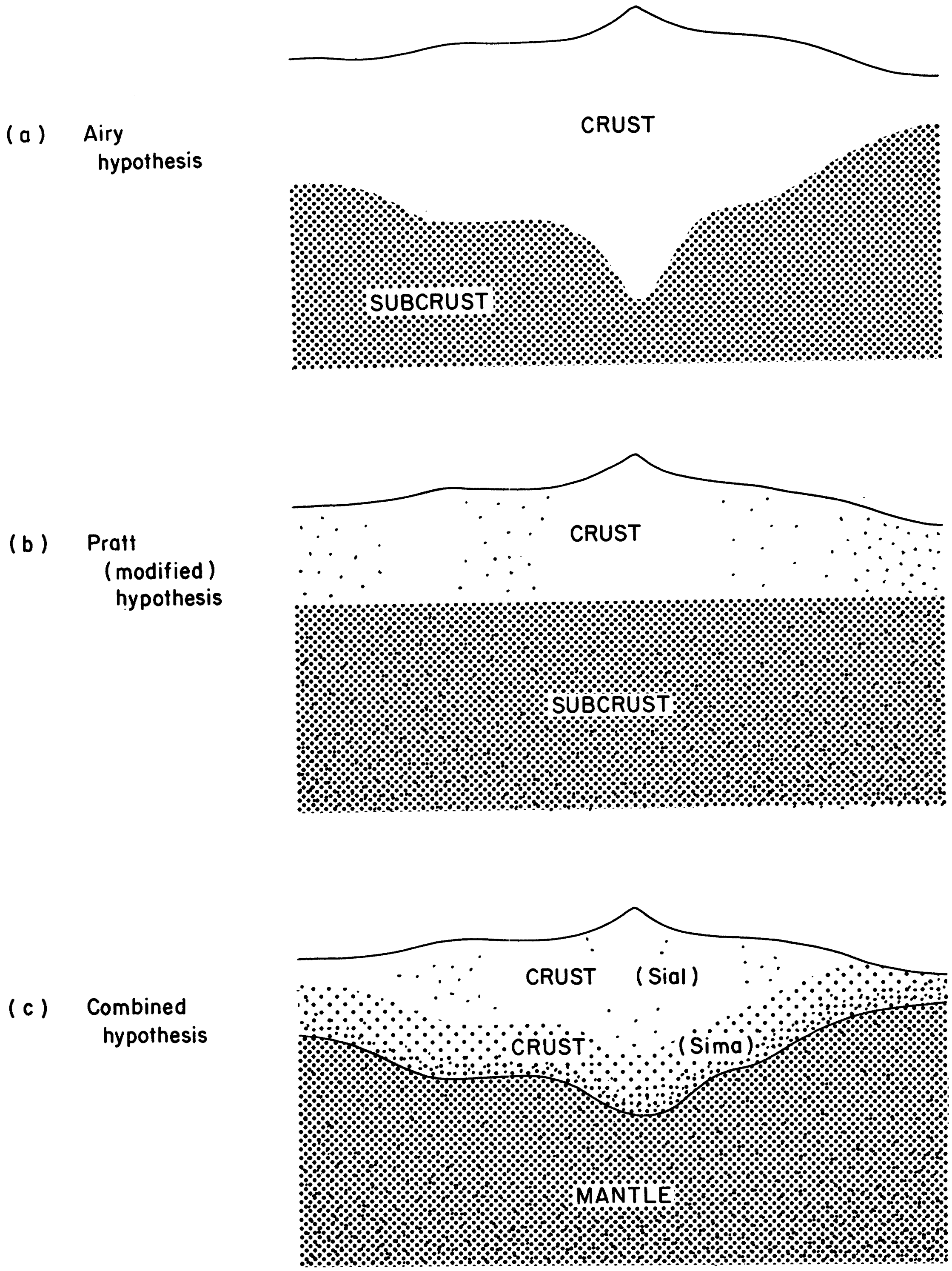



Fig. 1. Schematic diagrams of the earth's crust as implied by the theories of (a) Airy, (b) Pratt (modified), and (c) combined hypothesis. Rock density increases with increased density of stippling.

thick if an analogy may be made with the present ice sheets of Antarctica and Greenland. The maximum thickness of the Antarctic ice sheet is 4270 meters (14,000 ft), and that of Greenland is 3,300 meters (10,800 ft) (Bentley and Ostenso, 1961, p. 886; Holtzscherer and Robin, 1954, p. 196). The shape of the continental glacier was that of a flat-topped shield with relatively steep gradients along the margins.

The weight of this tremendous mass of ice piled on the earth's crust created a stress which exceeded the strength of the lithosphere, and, according to the concept of isostasy, the lithosphere sank into the weak layer below (the asthenosphere) until a condition of approximate equilibrium was again achieved. As the ice accumulated the increasing weight first caused the lithosphere to be deformed elastically in a basin-like shape; then, as the stress exceeded the strength of the crust and the asthenosphere, plastic flow occurred in the weak subcrustal layer.

The movement of plastic material from beneath the glacial area toward the ocean basins, the floors of which were rising due to the decreasing load caused by the progressive loss of water, was accompanied, according to many geologists (e.g., Jamieson, 1882, p. 461; Barrell, 1915, p. 13; Nansen, 1927, pp. 40, 42-44; Burger and Collette, 1958, pp. 227-240), by an upward bulging of the crust outside the area of depression. The formation of the bulge is explained by Nansen (1927, pp. 39-40) as follows:

> It is, however, obvious that when, within a certain area, the crust is depressed by deposition of sediments [ice] on its surface, this will cause an outward flow of mobile matter in

> the plastic substratum; but owing to the resistance caused by the great internal friction, this flow cannot extend over indefinite areas, but will at first be limited to the surrounding regions, where the surface will be somewhat elevated in a belt around the depressed area. The elevation will be highest near the latter, and will gradually decrease outward toward zero.

The existence of a noticeable peripheral bulge has been denied by other workers who pointed out that the high bending strength of the lithosphere would preserve a bulge to the present time, and that a permanent tilt should be recorded in the postglacial beaches south of their "hinge lines"—neither condition has been found. However, the apparent lack of a bulge may be explained if the peripheral bulge is so low and broad that it cannot be detected by present methods of field measurement.

An estimate of the maximum extent and magnitude of the depression of the land due to glacial loading may be gained from an examination of the limits of the Wisconsin glaciation as shown in Plate I and from a consideration of the simple formula

$$D = t\frac{d_i}{d_a} \tag{1}$$

where D = depth of depression, t = thickness of ice, $d_i$ = density of ice, and $d_a$ = density of the asthenosphere.

The Wisconsin continental glacier extended from its center in the latitude of Hudson Bay to the southern boundary of the Great Lakes Lobe which terminated in the southern half of the States of Illinois, Indiana and Ohio. It must be realized, however, that the limits of the crustal

depression did not coincide with the southern limits of glaciation. The depression was limited by the thickness of ice necessary to overcome the strength of the underlying crust. Near the edge of the ice sheet the ice was probably not thick enough to provide the necessary weight for depression; whereas, farther in from the edge, the ice was thick enough for its weight to cause elastic deformation, and still farther north the weight of the ice exceeded the strength of the lithosphere and asthenosphere so that plastic as well as elastic deformation occurred. With sufficient time the lithosphere under the glacier would be depressed until hydrostatic equilibrium was established.

At the center of the ice sheet, an approximate depth of depression may be calculated from the formula $D = t\frac{d_i}{d_a}$, if the following assumptions are made: (a) the ice thickness was c. 10,000 ft, (b) the ice density was c 0.92, (c) the density of the athenosphere is approximately 3.3, and (d) the isostatic adjustment was complete. With these qualifications, the depth of depression at the glacial center would be on the order of 2,800 ft, decreasing in magnitude southward as the ice thinned. The profile of depression was probably the inverse profile of the glacier surface.

## Glacial Unloading

The process of glacial unloading began after the regimen of the Wisconsin glacier had changed from a positive to a negative balance. The retreat of the glacier's terminus, as well as the thinning of the

ice sheet by melting of its upper surface, brought about the reversal of those processes described in "Glacial Loading." The first reaction of the depressed crust to the decreased weight of ice was an elastic recoil of the crust; this, in turn, was followed by uplift due to plastic flow in the substratum. Plastic deformation occurred when the melt waters of the glacier returned to the ocean, and as the load on the land decreased, that on the ocean bottom became greater and greater—once again disturbing the condition of hydrostatic equilibrium—which caused a reversal of flow of material in the asthenosphere.

The ice front retreated about 140 miles north of its southernmost extension (crossing the southern boundary of the Great Lakes watershed) before glacial margin lakes began to form between the southern moraines and the ice front. The glacier continued to retreat in a series of partial retreats and advances to the time of the Cary-Port Huron interval when, according to J. L. Hough (1958, p. 287), the ice front in the Great Lakes region probably extended from the vicinity of Oswego, New York, to the neighborhood of Beaver Bay, Wisconsin, on Lake Superior; passing near Gravenhurst, Ontario, the northern tip of the Saugeen Peninsula, the Straits of Mackinac, Escanaba, Michigan, and the southern end of the Keweenaw Peninsula.

During the time that the glacier was receding c 440 miles in a period of 2000-3000 years (Hough, 1958, p. 278) elastic and plastic deformation were acting to restore the southern glaciated areas to their pre-

glacial elevations. The amount of land uplift which occurred during this period may answer the point brought up by Sherman Moore (1948, p. 708) when he declared: "... The ice of the Wisconsin glaciation extended almost to the Ohio River, yet the old beaches show no differential movement below the hinge lines which cut across the Great Lakes."

The old beaches failed to show differential movement because the land south of the "hinge lines" had almost completely resumed its preglacial elevation before beaches were formed. This serves to emphasize the fact that the amount of land uplift revealed by differential warping of glacial lake strandlines since ice retreat is a minimum value and represents an unknown proportion of the total recovery from glacial loading.

The process of glacial lake beach formation has been used to explain two different concepts of the continuity of land uplift. Proponents of both views agree that the strong beaches were formed either during periods of relatively constant relationships between the water level and the land, or during periods of slightly rising water levels. However, opinions differ as to the way in which the constant relationships were maintained.

The more widely-held opinion is that the relationships were constant and shoreline features were formed during times when land uplift had stopped so that stability prevailed. When land uplift resumed, the shoreline features were warped in those areas where isostatic adjustment was not complete.

The second viewpoint, that shoreline features were formed during periods of continuous uplift when the rise of water level kept pace with the uplift of the land, has been summarized by the Norwegian scientist and explorer, F. Nansen (1927, pp. 47-48), as follows:

> The now raised post-Glacial strand-lines, beaches, and terraces of the formerly glaciated regions, have obviously been formed during periods of nearly constant relation between sea-level and land, or when the sea was rising slightly relatively to the land. In an earlier paper [1922] the author has tried to prove that such conditions were not created by any break in the upheaval, still less by any new depression of the land in late-Glacial or post-Glacial time, as assumed by most previous authors. Owing to the lag in the isostatic adjustment there must obviously have been so great an excess of "buoyancy" in the crust during the period of its upheaval that any temporary pause in the melting of the ice-cap, or even a temporary increase of it, cannot have stopped the uplift of the land, and still less have produced a temporary subsidence.
>
> The conditions for the incision of strand-lines, or the formation of marked beaches or terraces, have existed during periods when the sea-level rose at the same rate as the coast or slightly faster, and the coast-line remained more or less stable sufficiently long. ...

The progressive return of the earth's crust to approximately its pre-Wisconsin elevation is manifested by the northeastward shift of the areas of horizontality of the strong beaches (Whittlesey, Warren, Iroquois, Algonquin and Nipissing) in the Great Lakes region. Plate I shows the location of the zero isobase of each of the five strong beaches, the Whittlesey beach is the oldest (c 12,700 yrs B.P.). Each beach was horizontal when it was formed; subsequent upwarping northeast of the zero isobase indicates that uplift continued here long after it had ceased southwest of the zero isobase.

According to one concept, after upwarping of the older shoreline northeast of the zero isobase occurred, crustal movement must have stopped in order that the shoreline features of the succeeding lake be formed; if Nansen's concept is followed, the rates of uplift and rise in the lake's water level must have been synchronous in order for shoreline features to form. After the formation of the shoreline features of the younger lake, upwarping either began again or proceeded faster than the rise in water level, depending on which concept is followed, so that the shoreline features of the younger lake were warped. This process occurred for each of the glacial lake shorelines.

The last distinct postglacial strand line to show upwarping is the Nipissing, which ended about 3,200 years before the present time (Farrand, 1960, p. 125, Table III). The area of horizontality of the Nipissing beach outlines that portion of the Great Lakes area where pre-glacial elevations have been restored to approximately their former altitudes. The degree of restoration is probably not complete due to the thick overburden of glacial drift which covers the glaciated region south of the Canadian Shield.

The drift, composed of material carried to the area by the four continental glaciers, has an average thickness of about 300 feet in southern Michigan and northern Indiana (Leverett and Taylor, 1915, p. 61) and a maximum thickness of more than 700 feet in Michigan (Aker, 1938). The thickness of the drift deposited in the Great Lakes basins should

also be hundreds of feet. Although the portion of the total drift thickness contributed by the Wisconsin glacier is unknown, it was certainly appreciable and its weight would probably keep the bedrock from attaining its full pre-Wisconsin height.

The above situation in the Great Lakes region may be contrasted with the one which exists in the Canadian Shield—the source area of the drift. Material from the Shield was removed by the ice and deposited elsewhere, making lighter the load on the underlying bedrock. Because the weight which formerly existed in the central area of glaciation is now distributed either in the outer areas of glaciation or carried away to the oceans, isostatic adjustment, when complete, should allow the Canadian Shield bedrock surfaces to become higher in elevation than they were before glaciation.

## III. DETECTION AND MAGNITUDE OF UPLIFT

Land uplift in Fennoscandia and the Great Lakes region has been measured quantitatively by three methods: (a) by measuring the warping of former shorelines, (b) by comparing water-level records over a long period of time, and (c) by precise leveling. In addition, gravity measurements and earthquake intensities have been used in a qualitative way to both affirm and deny the existence of residual depression and consequent modern uplift in these areas.

### Warped Glacial Lake Shoreline Features

The most positive method of demonstrating the existence of postglacial uplift is by measuring the warping of the depositional and erosional land forms produced by the action of the former lake surface. Due to the length of time in which the upwarping action was able to act, the upwarp of the shoreline features amounts to tens or hundreds of feet as they are traced from south to north.

The shoreline features used to determine the amount of uplift include: beaches and bars (deposits of sand or pebbles accumulated by onshore and along-shore waves and currents), deltas, wave-cut and wave-built benches, wave-cut cliffs and outlet channels. These glacial lake features are now found at a higher elevation and farther inland than present lake features.

In order to cover the greatest area possible, the majority of the investigators who mapped the shoreline features of former lakes used altimeters or hand levels to determine their elevations. The inaccuracies inherent in the instruments and methods coupled with the difficulties of determining the elevation of the former water surface—i.e., of correlating wave-cut features with wave-built features of lakes whose surfaces varied several feet in elevation from year to year—result in elevations which are probably accurate from ± 5 to ± 10 feet. Although some elevations were determined by spirit level or by hand level from near-by known elevations, the uncertainities of measuring features formed by a fluctuating water surface remain; thus making an accuracy of better than ± 5 feet rather unlikely (Robinson, 1908, pp. 348-358).

Gilbert's (1890, p. 368) method of representing a warped plane was followed by G. De Geer (1892, p. 457), the Swedish glacial geologist, who connected points of equal deformation with a line which he called an "isobase." The isobase of zero deformation which marks the boundary between the area of horizontality of the glacial lake features and its area of warping was called the "hinge line" by J. W. Goldthwait (1908, p. 473) and subsequent workers. However, the term "hinge line" connotes a definite demarcation between the horizontal and warped areas which does not actually exist; as Farrand (1960, p. 9) has recently pointed out, "the apparent hinging effect shown in most profiles of former water planes (...) is produced by the exaggeration of vertical scale which is neces-

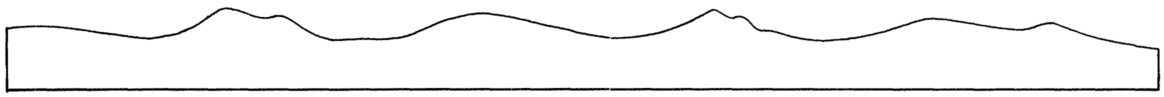
sary in such diagrams." Farrand (1960, p. 90) later called attention to the fact that the "isobase of zero uplift for the Nipissing beach ... is difficult to determine within 10 or 20 miles because of the extremely low slope of the water plane as it approaches horizonality [1:13,900]."

The difficulty of locating the position of the intersection of the warped and horizontal portions of glacial lake shorelines having gradients ranging from c 1:1,400 to 1:14,000 may justify substituting the term "transition zone" for "hinge line."

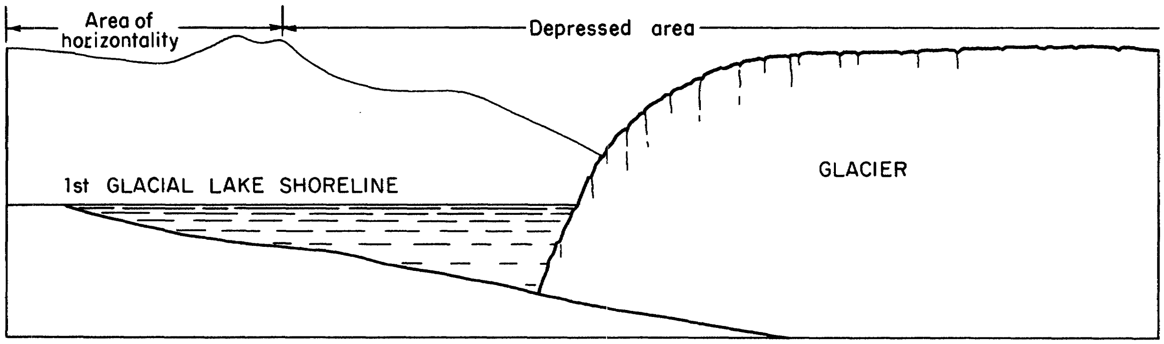
This problem of illustrating on a vertical profile the change from horizontal to upwarped lake shoreline features is one facet of the overall problem of representing in two dimensions a phenomenon (occurring on an ellipsoidal earth) which has extremely large horizontal dimensions when these dimensions are compared to its vertical extent.

The extreme shallowness of the depression caused by the continental glacier at its maximum may be illustrated by comparing the southward extent of the ice sheet of 1,300 miles with the possible depression of the earth's crust of 2,800 feet at the center of the glacier. The average gradient in this case would be c 1:2,450 or the slope angle would be c 1 min 24 sec.

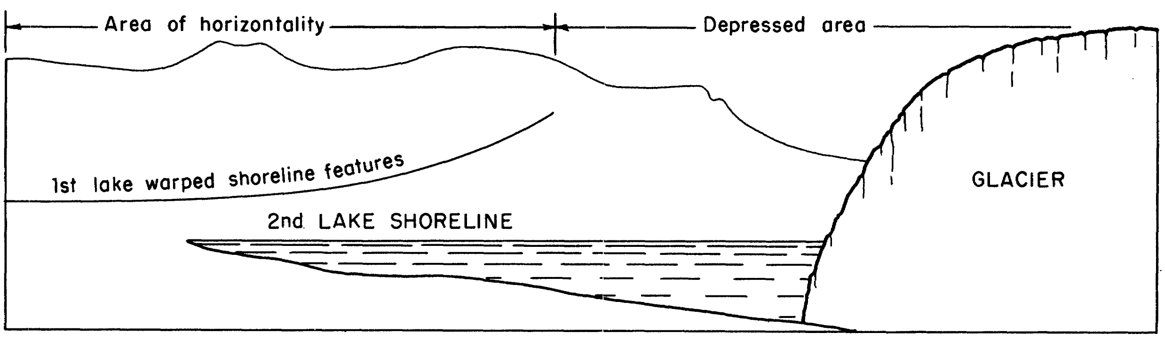
Distortions induced by the grossly exaggerated vertical profile necessary to show the relationships of horizontal and uplifted areas of shoreline features have led to the use of the term "doming" or "updoming" to describe the action of the land recovering from depression. An examination of Fig. 2 reveals that the "doming" is illusory, caused by the up-



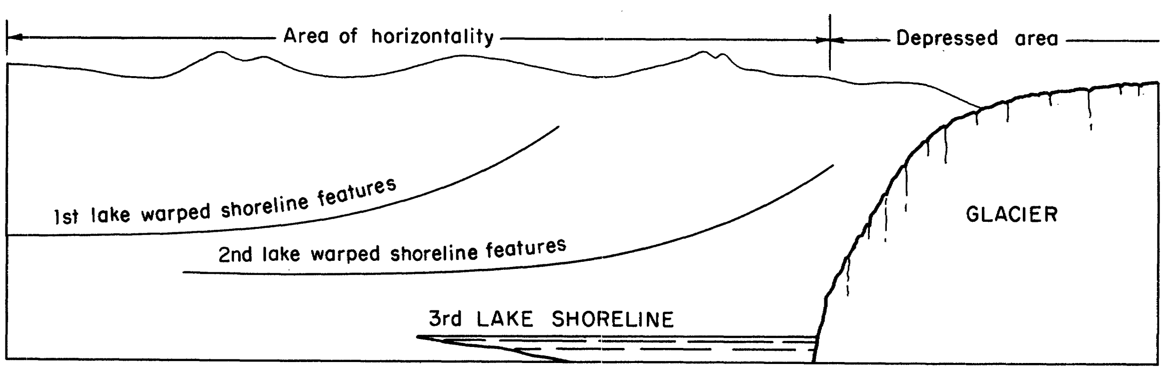
(a) Land sky line profile before glaciation.




(b) First glacial lake stage.




(c) Continued retreat of glacier– uplift of shorelift features.




(d) Continued recovery of land and warping of 2nd shoreline.

Fig. 2. Schematic diagrams showing recovery of the depressed regions and upwarping of shoreline features.

warping of sections of former shorelines. The crust which was depressed under the weight of the ice rises only until it assumes its preglacial elevation; the elevation of the land at the center of the ice sheet may be higher after isostatic recovery than it was before glaciation (see p. 31).

The glacial lakes were formed in topographical low areas of the regions depressed by the weight of the ice sheet; usually (as shown by the attitudes of former beaches) the lakes extended from non-depressed regions to the depressed regions in front of the glacier. The shorelines reached from an area of horizontality, across an area free of ice but still depressed due to the lag in isostatic recovery, to the glacier front. After a period of time in which the glacier retreated to a new position, another lake formed at a lower elevation than the first; isostatic recovery occurred and the depressed area rose to approximately its former elevation; carrying with it the former shoreline. Thus the former depressed areas are now essentially horizontal, although part of the former shorelines are now upwarped.

The positions of the isobases of zero deformation shown on Plate I demonstrates the fact that the zero isobases are almost parallel with each other and that the locations of the zero isobases show successively younger isobases to be northeast of the older ones.

Isobases found on maps depicting postglacial uplift of the land (Hough, 1958, Figs. 34, 42, 51; Flint, 1957, Figs. 14-1, 14-2, 14-5, 14-6, 14-9; Daly, 1934, Fig. 64; Sauramo, 1939, Fig. 1, etc.) are regional

isobases, and, by smoothing out irregularities, show the broad gently curving trends of deformation. However, detailed studies of the local trends of the isobases have revealed that the amount of uplift, as well as the direction of the trend, was influenced by geological and topographical features (De Geer, 1892, p. 458; Leverett and MacLachlan, 1934, p. 550; Sauramo, 1939, pp. 15, 21-23; MacLachlan, 1939, pp. 63, 80-82).

MacLachlan (1939, pp. 80-81) studied the Glacial Lake Warren shoreline and found that:

> ... The water plane of Lake Warren was not only deformed by northeastward tilting as indicated by straight line isobases connecting widely separated points, but there was also local deformation of the area along these isobases of regional tilt and this local deformation reflects the major details of buried structures.

In addition, the spacing of the regional isobases indicates that the former shorelines were not tilted as flat planes, but were warped upward into gentle curves. The progressively closer spacing of the isobases to the northeast shows that the concave profile of the shorelines became steeper to the northeast, and, consequently, that the rates of uplift increased in that direction.

Average rates of uplift for six shorelines in the Great Lakes region (Whittlesey, Warren, Grassmere, Algonquin, Iroquois and Nipissing) are given in Table 1. The rates were found by measuring from the zero isobase to the highest definite isobase of the shoreline being measured. The average rates do not illustrate the progressive steepening of the shoreline profiles to the northeast, e.g., the average rate of uplift for

TABLE 1

RATES OF UPLIFT OF FORMER BEACHES

| Former Beach | Age Approximate Years, B.P. | Modern Lake Basin | Measured | | Average Measured Rate, feet/miles | Average Rate/100 Miles, feet/miles | Source |
|---|---|---|---|---|---|---|---|
| | | | From | To | | | |
| Nipissing | 3200 | Huron | Walkerton, Ontario | Field, Ontario | 95/173 | 55/100 | Leverett & Taylor, 1915, pp. 458-459<br>Hough, 1958, Fig. 51 |
| | 4100 | Superior | Wakefield, Michigan, approximate | c. 4 mi N of St. Ignace, Island, Ontario | 95/194 | 49/100 | Farrand, 1960, Pl. IV |
| Iroquois | 8800<br>9600 | Ontario | East Gaines, New York | Pancake Hill, Ontario | 300/82 | 366/100 | Coleman, 1936, Map 45f |
| Algonquin | 9500<br>10000 | Huron | 1.5 mi S of Ruth, Michigan | 3 mi S of Little Current, Ontario | 408/151 | 270/100 | Hough, 1958, pp. 215, 223<br>Leverett & Taylor, 1915, Pl. XX, p. 411 |
| Grassmere | 10200<br>10500 | Huron | 2 mi N of Lexington, Michigan | Northline of Sanilac Co., Michigan | 50/25 | 200/100 | Leverett & Taylor, 1915, Pl. XX |
| Warren | 12200<br>12700 | St. Clair<br>Erie | Conneaut, Ohio | Spring Brook, New York | 140/121 | 116/100 | Leverett & Taylor, 1915, Pl. XVIII |
| Whittlesey | 12700<br>13200 | St. Clair<br>Erie | Ashtabula, Ohio | West Alden, New York | 182/140 | 130/100 | Leverett & Taylor, 1915, Pl. XVIII |

the Nipissing shoreline in the Superior basin is 0.49 ft per mi; whereas, Farrand (1960, p. 56) finds that: "It is horizontal south of Knife River, Minnesota, but slopes 0.38 ft per mi in the Tofte-Lutsen area, 0.42 ft per mi near Grand Portage, Minnesota, and 0.50 ft per mi in the Nipigon, Ontario, area."

Rates of uplift computed from the elevations of former shoreline features are based on quantities which could be the result of up to 13,000 years of land uplift; furthermore, the differences in elevation between the zero isobases and the isobases of maximum deformation are measured in tens or hundreds of feet. The magnitude of these quantities is great enough for elevations determined by ordinary methods of spirit leveling (corrected for meteorological effects and for the fluctuation of the modern lake datum) to be used in the calculation of accurate rates of past uplift.

This situation contrasts greatly with the determination of modern rates of uplift by means of precise leveling; or by means of water-level gage records; where the period of record is measured in tens of years and the magnitude of uplift is in hundredths of a foot, in tenths of a foot, and, in some cases, in feet. Under these circumstances, errors in the determination of elevations which would be insignificant in the calculation of rates of past uplift constitute such a large proportion of the total amount of modern rates of uplift that the modern figures could be valueless.

## Water-level Gage Comparisons

Modern land uplift values have been calculated from comparisons of water-level gage records (tide gage records and lake-level gage records) taken over a period of 50-100 years. The principle forming the basis for this type of computation is that of "water leveling;" which, as defined by the U. S. Coast and Geodetic Survey, is:

> A method of obtaining relative elevations by observing heights with respect to the surface of a body of still water. The surface of a body of still water, as of a lake, is a level surface (equipotential surface), and the relative elevations of objects along its shores may be obtained by taking the differences of their heights with respect to the surface of the water. ... (Mitchell, 1948, p. 46).

The comparison of heights taken from tide gage records furnished the necessary data for the computation of rates of uplift around the Gulf of Bothnia and the Gulf of Finland in Fennoscandia, and differences in elevation of lake-level gage stations have supplied information necessary for the calculation of rates of uplift in the Great Lakes region and the lake district of Finland.

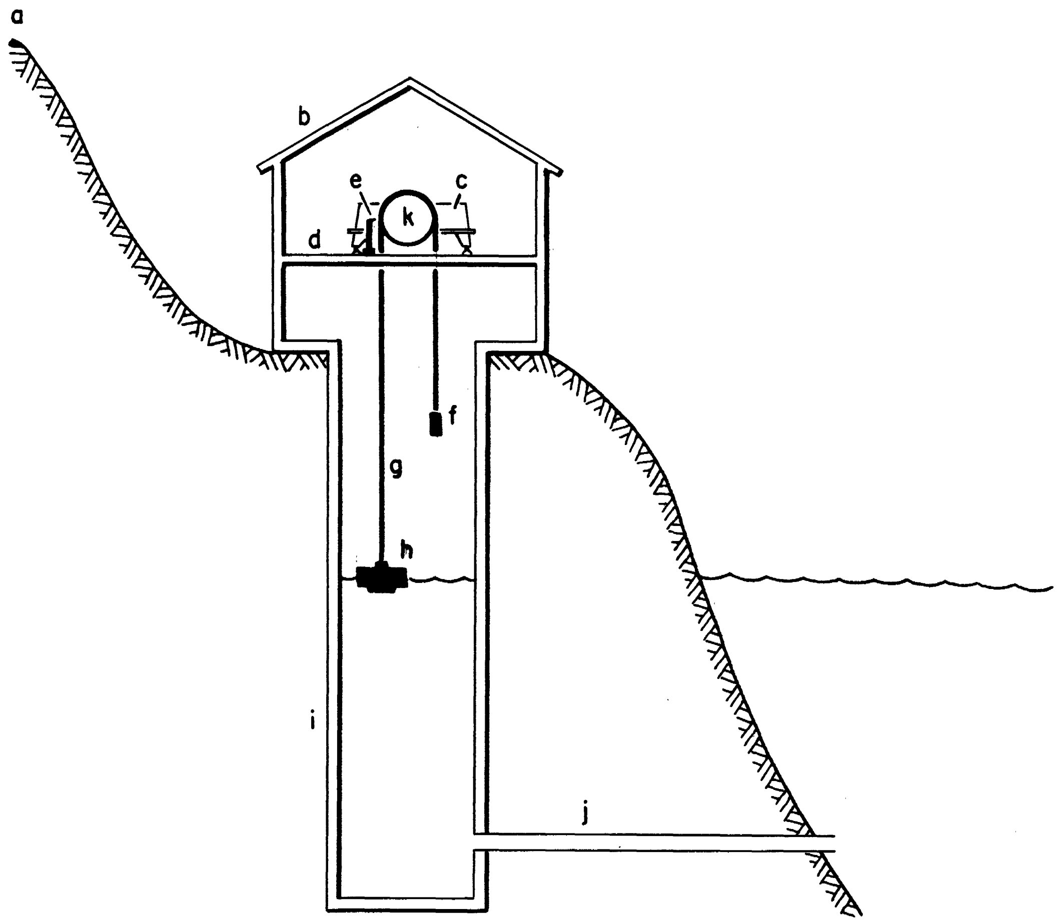
Tide gage records are used not only to provide a direct means of calculating rates of uplift, but are also used indirectly when uplift rates are determined by precise leveling. Mean sea level (MSL), the standard datum for elevations, is established by means of tide observations taken over a number of years; in addition to providing the standard datum, primary tide gage stations are used as starting and "tie-in" points in the precise leveling net (Marmer, 1951, p. 67; Hayford, 1922, pp. 131-132).

Great Lakes rates of land uplift are also influenced by this indirect function of tide gages determining mean sea level if absolute rates of movement are desired—lake-level gage records alone allow only relative rates of uplift to be found. Tide gage stations in the New York City area (Sandy Hook, New Jersey; Governors Island, New York; Fort Hamilton, New York; and the Battery, New York City) have been the starting points for level lines used to establish elevations in the Great Lakes region; therefore tidal records of the New York City area are important in the determination of Great Lakes absolute rates of uplift.

## WATER-LEVEL GAGES

The component parts of the water-level gage station illustrated in Fig. 3 are common to almost all permanent installations. A recording device is mounted on a stable platform situated over a stilling well which is connected to open water by a pipe of relatively small diameter. The stilling well with its restricted inlet eliminates short period fluctuations without affecting the recording of the water level. The recorder consists of two basic parts, one is a clock mechanism to move a roll of paper under a stylus at a uniform speed, and the other is a height registering mechanism with a float which, through a linkage of float-line and gear train, moves the stylus a distance which is proportional to the change in water level.

An index (zero) mark on the stable platform is connected by a double line of spirit leveling to three or more permanent bench




(a) Bench mark

(b) Gage house

(c) Water-level recorder

(d) Stable platform

(e) Index

(f) Counterweight

(g) Float line

(h) Float

(i) Stilling well

(j) Inlet pipe

(k) Pulley

*Note:* *Stylus and clockwork-roller mechanisms not shown.*

Fig. 3. Schematic diagram of a water-level gage installation. (In part, after Stevens, n.d.; Hela, 1953.)

marks. At regular intervals the leveling from bench marks to gage is repeated in order to detect any changes in the zero of the gage. Periodically, an observer, using a staff gage or electric contact tape, measures the distance from the index mark to the surface of the water; he records this figure and the time so that during tabulation of the record the automatic gage record may be correlated with the elevation of the index mark.

After the automatic gage roll has been removed from the recorder, hourly elevations are tabulated from the continuous curve of the recorder roll in order to provide a basis for computing daily, monthly and yearly mean water-level elevations.

Water leveling, the determination of mean sea level, and the calculation of rates of land uplift from water-level records are all based on the tacit assumption that the mean elevation of the water surface as determined by the record from the gage station represents the actual mean elevation of the body of water. This assumption would be very nearly true if the surface of the water body were a level surface (equipotential surface), and if the tabulated values of the water elevation were representative samples of the level surface elevations. However, the water surface is rarely, if ever, a level surface and its elevation, as revealed by water-level gage records, is affected by a number of factors whose influence must be removed or rendered insignificant if the gage readings are to an accurate representation of the actual elevation of the water surface.

Some of the factors which disturb the level of the surface of a body of water or distort its true elevation, i.e., meteorological effects, operator and instrument errors, benchmark and/or gage movements, are common to both sea and lake surfaces; whereas, other influences, i.e., the eustatic rise of sea level, density changes and tides, are important only in computing elevations of the sea surface.

Tide Gage Comparisons

The principle underlying the calculation of rates of land uplift by means of tide gage comparisons is a simple one—the elevations of certain fixed points along a coastline (tide gage index marks) are compared with a plane of zero elevation (mean sea level) over a long period of time. If the differences between the zero plane (MSL) and the elevations of the tide gage marks remain constant, no uplift has taken place; on the other hand, if the differences increase with respect to the zero plane, uplift has occurred; and the rate of uplift is found by means of the equation for a straight line

$$y = mx + b \tag{2}$$

where y = the differences in the elevation of the tide gage; x = the time in years; b = uplift at the start of the time series; and m = the angle coefficient, the value of the rate of yearly land uplift.

The principle is a simple one, but difficulty arises in practice due to the problem of establishing the zero plane; that is, the true mean sea level. Because the factors, e.g., meteorological effects,

tides, operator and instrument errors, influencing the determination of mean sea level vary their effects from one time to another, as well as from one geographical location to another, they must be discovered, their magnitudes computed, and their effects removed from the recorded data before an accurate mean can be found.

Requirements as to the degree of accuracy which is necessary for establishing mean sea level varies for different purposes—due to the very small magnitude of modern land uplift, about 0.008 ft/100 mi/yr (see page 91), the accuracy requirements which are necessary when dealing with this phenomenon are stringent; thus the effects of the disturbing elements must be removed until their residual influence is very small.

Tides

One of the factors producing the greatest deviation of the sea's surface from that of a theoretical equipotential surface is the tide, which is defined as: "The periodic rising and falling of the water that results from the gravitational attraction of the moon and sun acting upon the rotating earth." (Schureman, 1949, p. 36). The equipotential surface necessary for use as a datum plane is approached when the effects of the tide and meteorological factors are eliminated by using tide gage records to determine the mean sea level.

Because tide-producing forces vary on a daily, monthly and yearly basis, it is necessary that tidal records be taken over a number of

years before mean sea level can be established. H. A. Marmer (1951, pp. 63-64) of the U. S. Coast and Geodetic Survey states that:

> A period of 19 years is generally considered as constituting a full tidal cycle, for during this period of time the more important of the tidal variations will have gone through complete cycles. It is therefore customary to regard results derived from 19 years of tide observations as constituting mean values. ...
>
> If the mean level of the sea remained constant over long periods of time and if the coast were absolutely stable, we might expect sea level at any place determined from one 19-year series to be the same as that derived from another such series even if separated by a number of years. Apparently, however, this is not the case, and for precise purposes it is therefore necessary to specify the particular epoch used in the determination of mean sea level. ...
>
> For New York Harbor there are available 56 years of observations, from 1893 through 1948. This permits three 19-year series, 1893-1911, 1912-1930 and 1930-1948, the last two having the year 1930 in common. For the series 1912-30, sea level referred to a number of bench marks in the vicinity of the tide station was 0.09 foot higher than for the series of 1893-1911; for 1930-1948 it was 0.29 foot higher than for 1893-1911, and 0.20 foot higher than for 1912-1930.

It would appear from the above quotation that mean sea level derived from periods of 19 or more years would eliminate almost all of the disturbing influences produced by the tides and meteorological effects; however, the gradual rise of mean sea level at tide stations outside areas of known crustal movements points to an eustatic change in sea level; and, considering local areas, to residual meteorological effects of long period climatic changes.

A consideration of long period variations in mean sea level is important in the calculation of rates of land uplift by precise leveling where re-leveling is carried out 40-80 or more years after the initial

precise leveling. The long period rise in sea level may have two effects—both causing a relative subsidence of the land—if compensation for the rise is not carried out. In the case of tide gages and accompanying bench marks which are located in an area of land uplift, such as Fennoscandia, the failure to correct for long period changes in mean sea level will cause the rate of land uplift to appear to be too small because the zero reference plane is rising at the same time that the land is being uplifted. The rate of rise of mean sea level must be added to the rate of land uplift if the true rate of crustal movement is to be determined.

The second effect of apparent subsidence occurs when a series of bench marks are re-leveled after a number of years, and the calculation of elevations is made on the assumption that mean sea level remains constant over long periods of time. In this case, the zero datum is assumed to have the same relation to the tide gage bench mark for the second leveling as it had for the first leveling; whereas, it is actually closer to the bench mark. Because the zero datum plane is held constant, it appears that the bench marks are subsiding; although, no actual crustal movement has occurred. This effect of apparent subsidence may be illustrated by an example based on information contained in the quotation taken from H. A. Marmer (see page 46).

Mean sea level in New York Harbor rose 0.29 foot from 1902 (mid-point 1893-1911 series) to 1939 (mid-point 1930-1948 series)—if a line of precise levels were run in 1902 and again in 1939, and if it were assumed

that no change had taken place in the elevation of mean sea level; then the bench marks would appear to have subsided 0.29 foot in 37 years, or at a rate of about 0.78 foot per 100 years.

Meteorological Effects

It has long been known that the level of the sea is affected not only by astronomical tides, but also by the force of the wind which blows across the surface, causing a piling up of water on the lee shore and a lowering of water level on the windward shore. Although this effect of the wind has been known since ancient times, it was not until 1804 that the influence of barometric pressure on the level of the sea was demonstrated. In 1804, a Swedish physician named Schulten correlated changes in barometric pressure with variations in the height of water level in the Baltic Sea and discovered that at a given locality the greatest increase in height of the water corresponded to the greatest depression of the mercury column of the barometer. He found that the maximum variation of 2.5 inches of the mercury column was the equivalent of a change in sea level of 34 inches, which corresponds very closely to the theoretical ratio of 1:13.21. Schulten's measurements together with his observation that the rise in sea level always preceded the drop in the mercury column, led him to conclude that the change in level was due "to the <u>unequal</u> pressure of the atmosphere upon different parts of the surface; ..." (M'Culloch, 1845, p. 269).

Despite the fact that the term "meteorological effects" could be applied to changes in water level brought about by local additions of water to the sea by rain and river discharge, as well as by density differences caused by dilution of the salinity of the sea and temperature changes, it usually includes only the effects of wind and barometric pressure (see Fig. 4a and 4b).

Wind Slope

As wind blows over a water surface an interfacial stress is produced by the viscous drag of the moving air on the water and by the form drag of the waves and wavelets (Montgomery, 1952, p. 132). This stress causes the water to move in a general downwind direction until it reaches shallow water or the shore where a piling up of the water creates a slope of the water surface. The surface slope, in turn, creates a gradient or gravity current which flows beneath, and in opposite direction to, the wind-drift current.

Various authors have labeled this wind-induced surface slope (after corrections have been made for the barometric effect) a "wind slope," a "wind denivellation," a "wind tide," a "wind effect," a "windstau," and wind "set-up." The term "wind slope" best describes this phenomenon; as "wind denivellation," while the most precise term is probably too long to be commonly used; "wind tide" has the connotation of periodic rising and falling due to astronomical influences; "wind effect" is not definite enough; "windstau" when translated as an "accumulation" or "banking up"

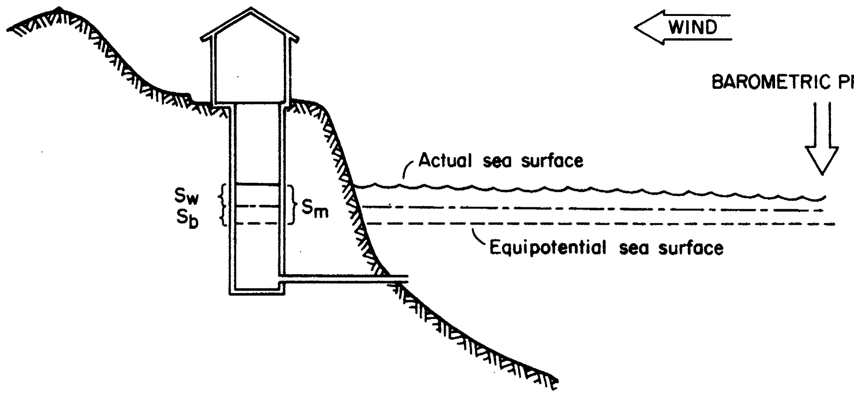



Fig. 4a. Effect of wind and barometric pressure on the surface of the sea.

EXPLANATION

Figure 4a. - $S_m = S_b + S_w$

Figure 4b. - $S = S_{ma} + S_{mb}$

*Where:*

$S_m$ = Meteorological effect
$S_b$ = Barometric pressure effect
$S_w$ = Wind slope
$S$ = Set-up
$S_{ma}$ = Meteorological effect at gage A
$S_{mb}$ = Meteorological effect at gage B

$H$ = Average equipotential waterdepth
$L$ = Distance between gages

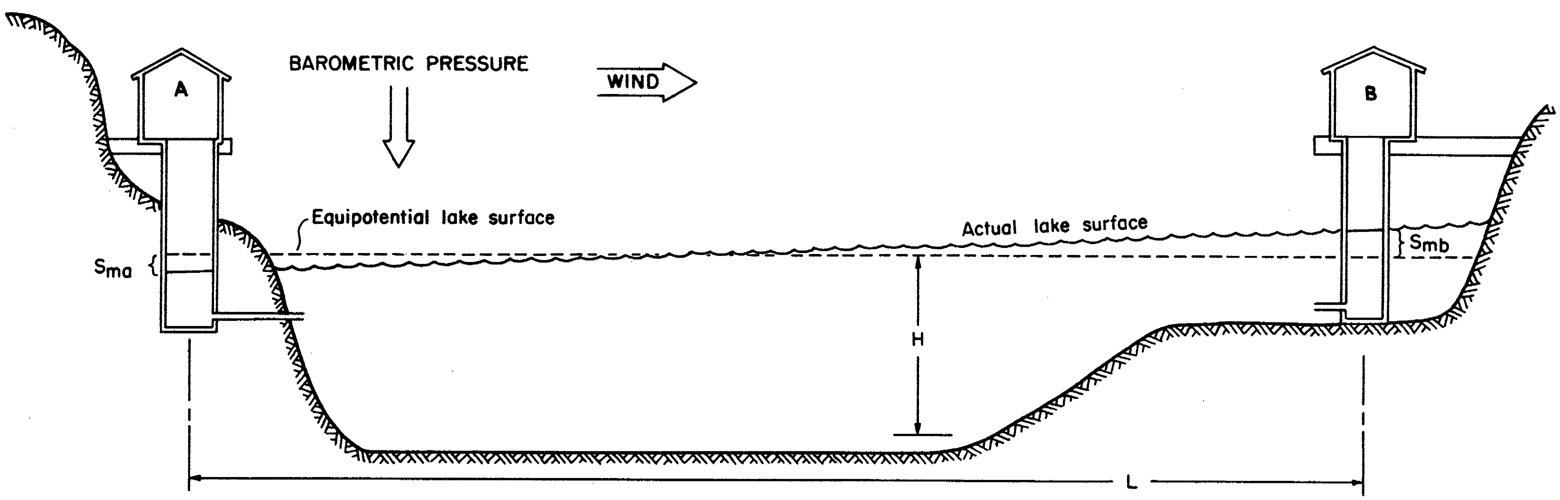



Fig. 4b. Set-up (total displacement of lake water surface from level) at lake-level gages.

by the wind has the proper meaning but is not as precise as "wind slope;" and the engineering term "set-up" is best used as

> ... either the displacement of the water surface at the leeward end of the channel with respect to the undisturbed level of the water or the difference of the displacement of the water levels at the windward and leeward ends of the channel, that at the windward end being negative (Keulegan, 1951, p. 365).

Two equations taken from G. H. Keulegan (1951, pp. 360, 576) illustrate the relationship which exists between the wind and a body of water when a slope is created through wind action. The theoretical development of the equations for determining the interfacial stress and wind slope assumes that:

(a) the air and water are homogeneous,

(b) the eddy viscosity is independent of depth,

(c) the stability of the air is nearly "indifferent," and

(d) an "equilibrium" state of the sea exists.

(Sverdrup, et al., 1942, pp. 473, 476, 491, 492, 495, 498; Montgomery, 1952, p. 133; Hutchinson, 1957, pp. 257, 265, 266, 267.)

The set-up, the difference in elevation of the water surface between the windward and leeward ends of a body of water, may be determined by the equation

$$S = \frac{n\tau_S L}{\rho g H} \qquad (3)$$

where

$$\tau_S = K_S \rho_a V^2 \qquad (4)$$

and where

$S$ = total set-up

$n$ = numerical coefficient based on $\frac{\tau_o}{\tau_s} + 1$, where $\tau_o$ = bottom stress and $\tau_s$ = surface stress

$\tau_s$ = tangential surface stress

$L$ = distance between the maximum and minimum water elevations

$\rho$ = density of the liquid

$g$ = acceleration due to gravity

$H$ = undisturbed depth of water

$\rho_a$ = density of moist air

$K_s$ = drag or resistance coefficient, also written $C_d$ and $\gamma^2$

$V^2$ = component of wind causing the maximum set-up

An accurate determination of set-up from the quantities involved in equations (3) and (4) is difficult due to the wide variances existing in the values for n, $K_s$ and the exponent of V.

The quantity n (also labeled x, H and $C_s$), the ratio of the bottom stress to the surface stress, varies from 1 to 1.5, depending upon the assumptions made by the investigator, and whether the flow is laminar ($n = 1.5$) or turbulent ($1 \leqslant n < 1.5$) (Hellström, 1941, pp. 25, 51; Keulegan, 1951, pp. 36, 61; Van Dorn, 1953, p. 253; Hutchinson, 1957, p. 273).

The extreme range of values for the drag coefficient $K_s$ is aptly illustrated by B. W. Wilson's (1960) review of the work of some 47

investigators dealing with wind-stress measurements. After "... adapting the laboratory data for wind speeds at 10-cm height (usually) to prototype conditions of wind speeds at 10-m height ..." and adjusting the results of various workers to the "$U^2$ Law," Wilson (1960, p. 3381) found that:

> The over-all average value (for strong winds) is $2.37 \times 10^{-3}$ with a standard deviation of $0.56 \times 10^{-3}$, ...
>
> The average value of $C_d$ for light winds is found to be $1.49 \times 10^{-3}$ with a standard deviation of $0.83 \times 10^{-3}$. ... The over-all range of values in this case extends from $0.4 \times 10^{-3}$ to $4.2 \times 10^{-3}$ and even $6.2 \times 10^{-3}$, though the latter value has been discounted in the averaging. ...

It may be seen from the conclusions reached in Wilson's paper that the determination of the value of the drag (or resistance) coefficient has improved only slightly since 1952 when R. B. Montgomery (1952, p. 134) declared "... the present evidence is so conflicting that at no wind speed is the resistance coefficient known confidently within half its value."

The third key quantity, the exponent of the wind velocity, as expressed in the general formula of equation (4), that is

$$\tau_s = K_s \rho_a (V - v_o)^m \qquad (5)$$

(where $v_o$ = the velocity of the surface water, which is small as compared to V and is dropped) is usually taken as the square power; although values from 1.5 to 5 have been used (Wilson, 1960, p. 3378; Hutchinson, 1957, pp. 273-275; Sverdrup, et al., 1942, p. 490).

The determination of the wind velocity term—usually considered as $V^2$—is further complicated by the fact that the set-up (as measured at any point) is the result of two component winds, a regional wind and a local wind. Therefore, it is necessary to determine the velocity of two winds whose influence varies in relative importance in response to changing velocities, durations and areal extent (Miller, 1958, p. 1; Gallé, 1925, pp. 917-918).

Theoretical determinations of the types of wind-driven currents in the ocean and their direction of motion with respect to the wind have been derived by V. W. Ekman and others from the Euler-Navier theory of laminar flow with the coefficient of viscosity in the equations being replaced by an "eddy" viscosity, a mechanical viscosity which depends upon the nature and state of motion of the fluid. The development of these theories also requires that the assumptions listed in a previous paragraph be made; i.e., that: (a) the air and water be homogeneous, (b) the eddy viscosity be independent of depth, (c) the stability of air and water be nearly indifferent, (d) equilibrium state of the sea exists, and in addition that, (e) the water be so deep that no bottom stress exists, and (f) that the horizontal stresses and their frictional forces not be considered (Sverdrup, et al., 1942, pp. 469-500; Hutchinson, 1957, pp. 259-273; Hellström, 1941, pp. 21-51; Eckart, 1960, pp. 1, 65-71, 95-97).

Because conditions in nature seldom conform to the assumptions underlying the theoretical basis for determining the types of currents and their

relations to the wind, because laminar flow rarely, if ever, occurs in large natural bodies of water, and because doubt has been cast on the validity of using the Euler-Navier theory with the replacement of $\mu$ (dynamic coefficient of molecular viscosity) by $\epsilon$ (coefficient of eddy viscosity) and $\nu$ (kinematic coefficient of molecular viscosity) by K (kinematic coefficient of eddy viscosity) for turbulent flow (Dryden, et al., 1956, pp. 389-390), the numerical values derived by Ekman for the angles between winds and wind currents, for the depths of frictional resistance, for the sizes of the bottom Ekman spiral, etc., at various water depths do not have the universal application that other investigators have given them.

The improbability of constructing an exact and complete mathematical model of the varying, interacting factors which exist in nature in the oceans and atmosphere demands a constant analysis and adjustment of theory when theoretical results conflict with observations of natural conditions. Very often empirical observations of the angles between wind direction and wind-drift currents in the oceans and in shallow bodies of water have been dismissed as being in error when they disagreed with Ekman's angle of 45°; in addition, the results of current measurements and directions of water slope have been questioned because Ekman's theory predicted very small or no angles between wind direction and current direction and water slope. Although Ekman's theory was the first and most important workable explanation of ocean currents, as with

any theory it must be evaluated in the light of new knowledge.

## Long Period Meteorological Changes

Changes in wind velocities and barometric pressures throughout time are important as the existence of land uplift revealed by tide gage records taken over a number of decades may be obscured by a progressive change in mean sea level caused by long period changes in the atmospheric circulation. This type of change in mean sea level can be brought about by a residual meteorological effect, as well as by eustatic change in sea level—neither of which is eliminated by averaging the tidal records over a full tidal cycle of 19 years (Marmer, 1935, pp. 30, 33, 48; 1948, pp. 201-02; 1951, pp. 63-64). At least two investigators (Kääriäinen, 1953, p. 27; Bergsten, 1930, p. 52) have pointed out that presumed variations in the amount of land uplift, as revealed by tide gage records corrected for known meteorological effects and eustatic change, are actually mean sea level variations resulting from long term climatic fluctuations.

The increase in mean sea level of 0.29 foot from 1902 to 1939 in New York Harbor (or 0.78 foot per 100 years) may be also partially or wholly explained by long range temperature and wind field changes.

Recent studies (Mather, 1954, pp. 287, 297; Baum and Haven, 1956, pp. 441-42, 447-48; Bjerknes, 1959, pp. 65-69; Landsberg, 1960, p. 1519) have shown that changes in the over-all circulation of the atmosphere, revealed by increased temperature and pressure changes, have occurred

in the last fifty years. During this period, which corresponds approximately with the time that continuous tide records of New York Harbor have been kept, the temperature over the Northern Hemisphere has increased and the pressure differences in the North Atlantic off the east coast have also increased.

The water supplied by the melting of the glaciers and the increased heating of ocean waters shown by the increased annual temperature may be the chief causes of a eustatic change of sea level amounting to about 11 cm/100 years (Gutenberg, 1941, pp. 729-30; Kuenen, 1950, pp. 532-35). A eustatic rise of sea level of this magnitude would increase the elevation of mean sea level in New York Harbor by 0.13 foot from 1902-1939.

The height of mean sea level in New York Harbor is affected primarily by astronomic tides and by water piled up by barometric pressure differences and the wind. Another factor which may influence the height of mean sea level at this location is variation in the discharge of the Hudson River—the discharge averages 26,000 cubic feet of fresh water per second at the Narrows, according to H. A. Marmer (1935, p. 2).

The barometric pressure effect and wind slope are composed of local and deep water components, both of which depend upon large scale atmospheric pressure differences. If mean sea level is derived from 19 years of tidal observations, the meteorological effects as well as the astronomical tides should be eliminated. However, if a progressive increase in pressure and geostrophic wind has taken place since the 1890's as

suggested by Bjerknes (1959, p.69), the residual effect of the increased piling up of water would be a rise in mean sea level. This increase could account for the 0.16 foot of mean sea level increase at New York remaining after the 0.13 foot change due to the eustatic rise of sea level had been accounted for.

Effect of Tide Gage Location

Primary tide stations which provide the necessary data for the computation of land movement, as well as for furnishing end points of precise leveling lines, are usually located near coastal cities and towns which are almost always built along estuaries and harbors. The factors that influence the elevation of mean sea level (tides, wind slopes and barometric pressure differences), have their greatest effect at those places where the water is shallow. In addition, the phenomenon of resonance which Proudman (1954, p. 200) calls: "the primary cause of the pronounced amplification (of the tide) observed in some gulfs and estuaries ..." occurs in bays, harbors and estuaries. In other words, in many cases primary tide gages are situated in those areas where changes in the terrestrial and submarine topography will have the greatest effect (Harris, 1907, pp. 435, 453, 455; Hayford, 1922, pp. 123, 124; Marmer, 1935, pp. 15, 43, 52; 1951, pp. 23, 45; Sverdrup, _et al_., 1942, pp. 539, 554, 562; Harris, 1954, p. 45; Proudman, 1954, pp. 199, 200, 202; Defant, 1958, pp. 68, 75).

Land uplift, due to its small magnitude (e.g., 0.75 foot/100 miles/100 years in the Baltic region), cannot be accurately measured unless index marks are compared with mean sea level over a period of several decades. If mean sea level (as determined by tide gages) changes during this period, the variation must be compensated for before land uplift can be calculated. During the decades in which the records are being taken, natural and man-made changes occur in the coast line and in the submarine topography which affect the range of the tide (Marmer, 1951, pp. 132-133). For example: the dredging of channels and dumping of spoil in shallow water; the filling in of shallow areas to extend the shore; the building of breakwaters, groins, piers, etc.; the growth of spits, bars and deltas; all change the configuration of the bottom and the shore, which in turn influences the height of the tide and of wind setup thus effecting the determination of mean sea level.

Two additional factors which may influence the determination of mean sea level at tide gages which are located in estuaries and straits are: (a) variations in the discharge of the stream, and (b) the difference in range of tide on opposite shores of a strait due to the deflective force of the earth's rotation (Marmer, 1935, pp. 19, 21, 57, 67-68; 1951, p. 45; Jensen and Sinding, 1945, pp. 16-19). Adjustments must be made for these factors when the records of two different tide gages are compared; or when records covering a number of decades from one tide gage are compared.

Instrument and Operator Error

The use of modern recording gages, modern operating procedures, and modern methods of record reduction have reduced the limits of error in the determination of mean sea level to negligible proportions for ordinary purposes; however, the computation of the rates of land movement from water-level records must use still more accurate methods because of the very small magnitudes involved. An additional problem stems from the fact that calculation of rates of crustal movement requires that mean sea level figures derived from relatively accurate modern instruments be compared with mean sea level determinations of forty, fifty, or more years ago—a period when neither the instruments nor the procedures were as precise as those of today. In order to evaluate the accuracy of water-level records, it is necessary to examine the errors which may have their source in the recording instrument and its operators.

Errors may enter in the determination of mean sea level in one or more of the following steps: (a) in the recording of relative sea level by the automatic gage, (b) in the recording of "absolute" sea level by the operator using a staff, hook, or electric tape gage, and (c) in the reduction of data from the continuous curve of the automatic water-level gage to daily, monthly, and yearly means. The discussion of instrument and operator error will not include the effects of obvious gross errors resulting from equipment malfunctions (e.g., leaky floats, improperly calibrated staff gages, freezing of float in the stilling well, etc.),

or personnel blunders (e.g., failure to read and record numbers correctly, failure to keep stilling well inlet clear, failure to take staff gage readings, errors in computations, etc.).

Water-level recorders, being float operated instruments, are subject to certain errors inherent in their construction. The errors are usually very small in instruments of modern design with large floats and light lines and counterweights; they assume much greater proportions, however, in the more crude instruments of 50-100 years ago.

As may be seen in Fig. 3 (p. 42), the float, through the medium of the float line and counterweight, performs work in operating the recorder pen. Owing to the friction in the instrument there is a lag between the force being applied by the water and the recording of the water level on the recorder chart. If the index is set while the float is rising, the rising stages will be recorded correctly, but the falling stages will be above the true level by the amount of the "float lag;" if the index is set for a falling stage, the rising stage will be low due to the lag.

When the float rises, part of the float line passing over the pulley adds its weight to the counterweight; thus lifting the float and causing the index pen to register a height greater than the elevation of the water level. When the water level goes down, the weight of the increased length of line is added to the float, causing the pen to record an elevation lower than the actual water level. If the counterweight and the line enter the water, their weight will be reduced by buoyancy; the float

will sink deeper into the water and the recorded water level will be too low (Stevens, n.d., pp. 20-27; 1919-1920, pp. 394-395; Corbett, et al., 1943, pp. 183-189).

The magnitude of the above errors may be computed by the following empirical formulas from J. C. Stevens's Hydrographic Data Book (no date, pp. 27-28). Stevens's formulas, which give the errors in feet with instruments using lead counterweights and steel float lines, are quoted below:

Maximum error due to float lag $= 0.37 \frac{F}{D^2}$ .......(7) (6)

Error from submergence of counterpoise $= 0.017 \frac{c}{D^2}$ ......(14) (7)

Error from line shift with counterpoise in air $= 0.37 \frac{u}{D^2} \Delta H$ ....(11) (8)

Error from line shift with counterpoise submerged $= 0.34 \frac{u}{D^2} \Delta H$ ....(15) (9)

in which

$F$ = force (pull on float line) in ounces to move index
$D$ = diameter of float in inches
$u$ = weight of float line in ounces per foot
$c$ = weight of counterpoise in ounces
$\Delta H$ = change in stage in feet from previous setting.

Float records may also be affected by changes in humidity which can cause an expansion or contraction of the recorder paper, or, in those instruments using hemp float line, which cause a change in the length of the line. If the index pen records on the gage paper in a humid environment, where the paper is expanded, and measurements of the water stage are taken from the record in a normal environment, where the paper has resumed

its normal dimensions, an error will be incorporated in the readings. The error can be compensated for only if two base line pens (a fixed distance apart) record in opposite margins of the chart. In this case the actual distance between the margin lines can be compared with the known fixed distance and the corrections computed (Stevens, n.d., pp. 32-38; Chrystal, 1908, pp. 361-370).

The role of the operator in the recording of relative sea level by the automatic gage has been summarized by J. C. Stevens (n.d., pp. 39-40) who said:

> <u>The Human Equation</u> constitutes the greatest possible source of error. Incorrect gage reading, inaccurate setting of pens and pencils, failure to wind the clock, failure to start clock after being wound, failure to put stylus on the paper, wrongly attaching float so that pen moves up when it should go down, failure to release set screws or to tighten them as the case may be, failure to note gage reading and time on record sheet; failure to see that inlet to well is open; failure to oil bearings occasionally, or the use of gummy oil, are among the few things that all too frequently result in erroneous or incomplete records.

The records of relative heights of sea level are changed to actual sea level elevations by comparing elevations on the gage record with separate readings made simultaneously by the operator with a staff, hook or electric tape gage at periodic intervals. The separate height determination measures the distance between an index mark on the water-level recorder and the surface of the sea. Because the index mark could, and often does, change due to accident, replacement of the equipment, etc., it is essential that the elevation of the index mark be tied by precise

spirit leveling to three or more permanent bench marks. It is obvious that for a study extending over a number of years, it is of utmost importance that regular connections be made between tide gage and bench marks in order to detect any change in the elevation of the index mark; probably one of the greatest errors in the determination of mean sea level over a long period of time is the failure to check the height of the tide gage index with its bench marks.

Other errors which may occur in the determination of "absolute" sea level by means of a staff gage are those due to the "error of the interval" of the staff gage and the "personal error" of the observer.

The "error of the interval" is, according to R. Gibbs (1929, p. 71), "... the same as the probable error of the last figure, namely one-quarter of the interval." H. A. Marmer (1951, p. 30) in speaking of U. S. Coast and Geodetic Survey procedure, states that: "The observer reads the staff to the nearest half tenth of a foot if the water is free from waves, or to the nearest tenth giving the highest and lowest readings." In this case the error should be ±0.012 foot or ±0.025 foot.

The "personal error" of the observer results from the particular way in which an observer takes his observations; e.g., the observer may always assume a certain position, so that his eye is a little above the index mark; thus introducing a degree of parallax which would differ from that in the reading of another observer; or one observer may tend to mentally subdivide the interval between the graduations so as to favor

recording even tenths of a foot, whereas another observer may favor recording half tenths. Thus, if "... the maximum error of any function due to errors in the variables is the sum of the errors due to each separately" as stated by R. Gibbs (1929, p. 77); then in the course of 50-100 years the sum of the observers' "personal errors" and of the "errors of the interval" could be significant.

Errors in the determination of mean sea level which originate in the tabulation of mean values from the continuous gage curve (excluding errors in calculation) may be classed under three headings: (a) sampling error, (b) errors of interval, and (c) errors of interpretation. These errors are probably of insignificant size for short term calculations, but their effects taken over a period of fifty or more years may be appreciable—apparently no studies as to their significance have been published.

The gage record of an automatic tide gage is a continuous sample of the fluctuating surface of the sea; if the effects of the disturbing factors were removed from the trace of the gage, the remaining curve would be a representative sample of mean sea level. If the effects of the disturbing elements and instrument errors are not removed from the gage record, a primary sampling error occurs. Furthermore, monthly and yearly averages are not compiled from the irregular gage trace, but are compiled from hourly tabulations taken from the curve. The discrepancy between the hourly values of sea level and the values obtained from the integrated area under the curve may be called the secondary sampling error.

As monthly means are computed from the hourly tabulation, yearly means from the monthly, and 19-year means from the yearly; the samples become less and less representative of the actual elevations of the sea (this assumes that the effects of the disturbing elements have been removed, and that the discrepancies are due solely to using averages based on hourly tabulations and other averages rather than being based on the continuous curve). The error arising from these procedures is a sample averaging error.

The errors of interval in the tabulation of mean sea level occur in two places: (a) in determining the factor used to reduce the gage trace to a fixed datum, and (b) in making the hourly tabulation from the trace. The values for the height of the tide at the time of the staff gage readings are measured (to tenths and half tenths of a foot) from the preliminary datum line to the curve with a reading scale graduated to the same scale as is used on the tide gage. This height (the relative height) is subtracted from the staff gage reading (the absolute height); the differences are summed and divided by the number of readings to obtain the mean difference. The mean difference, together with a constant for fixed datum, is added to the preliminary datum setting to obtain the correct height of the base line of the gage curve. The hourly readings are then measured to tenths and half tenths from the base line to the curve.

The gage trace (if the stilling well inlet is not small enough) is not a smooth curve, but, instead, is an irregular curve with small sharp fluctuations ("saw teeth") due to the action of waves and swells and

larger irregularities due to seiches (periodic oscillations of the water body)—the irregularity of the trace makes tabulation difficult. Therefore, "For use in the determination of tidal datum planes it is preferable to consider a smooth curve through such irregularities and tabulate the hourly heights directly from this smooth curve" (Marmer, 1951, p. 41).

The error of interpretation is the algebraic sum of the differences between the actual tidal curve and the smooth curve. Another source of interpretative error takes place when an interpolation is made for breaks in the tidal record. As in the previous case, the error is the algebraic sum of the differences between the interpolated curve and the actual sea level.

The influence of instrument and operator error is relatively small in modern records; nevertheless it is still too large if accurate uplift rates are to be computed. Rates of postglacial crustal movement in Fennoscandia illustrates the need for very accurate measurements. The rate of uplift 87 miles from the former ice center is 2.68 feet per century (Kääriäinen, 1953, p. 59, Fig. 14) or 0.03 foot/year (0.002 foot/month), and only 450 miles from the ice center uplift ceases; the average rate is 0.75 foot/100 miles/100 years. The small magnitudes of these uplift rates emphasizes the fact that the cumulative effects of the various factors which distort the true value of mean sea level must be considered and eliminated, or at least compensated for, if accurate rates of uplift are to be determined.

LAKE LEVEL GAGES

Records of pairs of lake-level gages have been the basis for crustal movement studies in the lake plateau of Finland and the Great Lakes region of North America. The Finnish lake study of A. Sirén in 1951 utilized the principle that the means of lake-level elevations, corrected for meteorological effects and the effect of slope due to discharge, would provide a level surface for the comparison, over a number of years, of two gages which were remote from each other. When the average values of the gage differences are plotted against time and the points connected by a straight line, the slope of the line gives the average land uplift.

The calculation of rates of uplift in the Great Lakes area by various investigators have followed the method of G. K. Gilbert (1896-97)—using the procedures described on pages 7-8, which briefly, is that elevations of pairs of lake gage stations are measured from a level surface (the lake surface), and the differences between the elevations of the gages plotted for a period of time. If a line of best-fit through the points has a slope, land uplift exists. When this method is used, no corrections are made for the effects of disturbing agents on the lake surface nor are corrections applied to the gage readings; it is assumed that the lake surface is level during the summer months (Comstock, 1876, p. 5; 1882, p. 595) (see Appendix I). The fact that each rate calculated by this method depends upon the records of two gages brings out the importance of detecting and removing those factors which distort the recording of true lake

level at each gage station.

Lake level gages and the procedures used to convert their recording curves to mean lake level elevations differ only in minor detail from tide gages and tide gaging procedure; therefore, the discussion of the factors which influence tide gage records also applies to lake-level records.

## Tides

Astronomical tides on those lakes large enough to exhibit detectable tides are measured in inches, whereas ocean tides are measured in feet. In the Great Lakes, Defant (1958, Table 4) shows Lake Erie as having a spring tide of 8.0 cm (0.26 ft), Lake Michigan of 7.3 cm (0.24 ft), and Lake Superior of 5.9 cm (0.19 ft).

The effects of tides of this magnitude should be very small, unless the lake-level gages are located in shallow water or in sites with converging shores; under these circumstances the tidal range would be increased. Rates of crustal movements in lake regions are computed from the differences in elevation of two gages; if dredging, construction of breakwaters, etc., occurred at one or both of the gage sites, it is possible that the change in the range of tide would appear in the gage height differences to be incorporated in the rate of uplift.

## Meteorological Effects

The influence of wind and barometric pressure differences was discussed in many of the early papers dealing with fluctuations of the Great

Lakes (e.g., Dwight, 1822, p. 96; Clinton, 1827, pp. 292, 293; Whiting, 1831, p. 214; Hall, 1843, p. 410; Mather, 1848, p. 1617; Whittlesey, 1859; Lachlan, 1855, pp. 165, 168, 172). These investigators of the late 18th and early 19th century observed the increase in the depth of water which occurred on the eastern shores of the lakes with prevailing westerly winds; were aware that barometric pressure differences piled up water in the area of lower pressure, and that this created seiches; and described the effects of shallow water and converging shores on wind slopes and seiches. Later studies of wind slope and barometric effect were concentrated on Lake Erie which produces greater wind slopes than any of the other lakes due to its shallowness, its long narrow shape with pointed ends, and its alignment with the prevailing winds (Blunt, 1897; Henry, 1902; Hayford, 1922; Hayford, 1923; Hellström, 1941, pp. 115-128; Keulegan, 1953; Hunt, 1958; Gillies, 1959).

Wind slope in the Great Lakes, as in the ocean, varies directly with the square of the wind velocity and inversely with the depth of water (see p. 51). In the formula (3) for setup

$$S = \frac{n\tau_S L}{\rho g H}$$

the undisturbed depth of water H is taken as the average depth of water along length L (e.g., in Lake Erie, H equals 58 feet); however, the establishment of "thermoclines" in the Great Lakes during the summer months may require a modification of the usual definition of H.

During the summer months in the Great Lakes a thermal stratification of the water in which an upper layer of " ... more or less uniformly warm, circulating and fairly turbulent water termed epilimmion, ..." is divided from "... a deep, cold and relatively undisturbed region termed the hypolimmion..." by the "thermocline ... defined as the plane of maximum rate of decrease in temperature ..." (Hutchinson, 1958, pp. 427-28). (Eckart, 1960, pp. 69-71). The depth of the thermocline is about 50-100 feet in Lake Huron and in the deeper portions of Lake Michigan and 20-50 feet in the shallow southern basin of Lake Michigan. (Ayers, et al., 1956, pp. 9, 41, 66; 1958, pp. 5, 31, 54, 80). The thermocline in Lake Erie is similar to the thermocline in the southern basin of Lake Michigan, usually being from 25-45 feet deep in the more shallow western two-thirds of the lake and 45-60 feet deep in the eastern third. At times during the summer the epilimmion extends to the bottom (up to 60 feet) in the central and western parts of Lake Erie, and maintains this depth across the deeper eastern third of the lake (Powers, et al., 1959, pp. 150-164). Presumably Lake Ontario has about the same depth to the thermocline (20-100 feet) as occurs in the deeper portions of Lake Michigan and Lake Huron (Hachey, 1952, pp. 326-328).

The significance of the depth of the thermocline is that "... the boundary between the two layers acts as if it were a temporary bottom" (Hellstrom, 1941, p. 112). In other words, during the summer when the lakes are stratified, the depth of water H in formula (3) could be considered as the average depth to the thermocline rather than the average

depth to the actual bottom. This concept is reinforced by observations made on the Scottish Lochs Ness and Gary (Murray, 1908, pp. 416-417; Wedderburn and Watson, 1908-09, pp. 629, 635; Wedderburn, 1909-10, pp. 312, 317, 319); Lake George, New York (Langmuir, 1938, pp. 121-123); and the Sakrower and Walchensee, Germany (Hutchison, 1957, pp. 287-288).

If the thermocline acts as a quasi-bottom, and since the depth to the thermocline is approximately the same in all of the Great Lakes, the amount of deflection between wind direction and surface current for Lake Erie during the summer months should be representative of the amount of deflection for the other lakes.

H. L. Langhaar (1951, pp. 279-280) has suggested that the total wind slope in lakes is made up of two component parts, a "statical tide" and a "dynamical tide." He declares that:

> The tide at the leeward end of the lake is the superposition of the tide due to the seiches and the statical tide that the wind would maintain if it persisted indefinitely. The tide due to the seiches will be called the "dynamical tide." The total height h of the tide at the leeward end of the lake is $h = h_s + h_d$, ... the term $h_d$ [dynamical tide] varies periodically with time.
>
> The maximum value of the ratio $h_d/h_s$ depends upon the planform of the lake, and upon the rate at which the wind develops.

Differences in elevation (corrected for barometric pressure effect) which are recorded by two gages over a number of years consist of a component resulting from the differences in the average height of water-level fluctuations produced by seiches at one gage being subtracted from the average height of water-level fluctuations produced by seiches at the

other gage (the "dynamical" portion), and a larger component made up of the net differences in water-level caused by the force of the wind (the "statical" portion). The magnitude of both components would be influenced by changes in the gage site environment occurring over a number of years (see pp. 58-59, 73-75).

The barometric pressure effect on the Great Lakes is of less importance than it is on the oceans owing to the smaller pressure gradients which exist over the lakes. Over the summer month period the differences in barometric pressure, and thus the barometric effect, between two gage sites on the Great Lakes has an order of magnitude of $10^{-2}$ or $10^{-3}$, whereas the order of magnitude of the net wind slope during the summer months is $10^{-1}$ (see Table 6, Appendix II, p. 179), e.g., if the effects of convergence and resonance are not taken into account, the barometric effect between Toledo and Buffalo on Lake Erie ranged between 0.002 foot and 0.017 foot for the summer months, 1950-59.

## Effect of Lake-Level Gage Locations

Lake-level gages, like their counterparts in the oceans, are usually located near population centers. This means that almost all gages are in harbors or bays, within river mouths, or within a river mouth located in a harbor or bay; e.g., in Lake Ontario the gages at Kingston and Cape Vincent are situated on the north and south channels of the St. Lawrence River; in Lake Erie, Buffalo is at the very narrow eastern end of Lake Erie and at the entrance of the Niagara River and Toledo lies at the

apex of the converging shores of Maumee Bay and at the mouth of the Maumee River; in Lake Michigan-Huron, Collingwood, Ontario is in Nottawasaga Bay, Thessalon, Ontario, is at the western end of North Channel and Mackinaw City is on the Straits of Mackinac; in Lake Superior the key gage at Point Iroquois is at the mouth of the St. Marys River at the southeast end of Whitefish Bay; Port Arthur is within Thunder Bay at the outlet of several rivers and Duluth is within Superior Bay at the outlet of the St. Louis River.

The discussion on pages 58-59 of the effects of converging shores, shallow water, and resonance on the piling up of water by wind slope and barometric effect also applies to lakes. Man-made and natural modification of the shores and underwater topography during the last 100 years have probably been as extensive in the Great Lakes regions as in ocean ports, which would result in a progressive change in lake level elevations being incorporated in the gage records.

Recent advances in telemetering equipment used in oceanography and space satellites suggests that certain key water-level gages on each of the Great Lakes could be located well off-shore in deep water; from these sites wind velocities, barometric pressures, temperatures and water-surface elevations could be automatically determined, transmitted and recorded. The location of water-level gages away from shallow water, bays, harbors, etc., would decrease the effects of convergence and resonance; thus the errors caused by meteorological effects, tides, river discharges and man-made changes would be greatly reduced. The recording of

temperature, wind and barometric pressure data at each of the key gage sites would provide the necessary information for the correction of the remaining meteorological effects.

Instrument and Operator Errors

Errors in the recording, correlating and reduction of lake-level gage records are of the same nature and order as those found in tide gage records; therefore the discussion of instrument and operator errors on pages 60-67 will also apply to lake-level gaging. Again it must be emphasized that rates of land uplift are computed from records which include those taken 45 or more years ago when neither the instruments nor the procedures were as refined as those of today, and errors which are very small in modern records are of much greater proportions in the older records.

The "error of the interval" of lake-level records will be smaller than that found in tide gage records because both staff gage readings and tabulated values are given in hundredths of a foot rather than tenths or half-tenths of a foot. The errors of interpretation caused by the replacement of the actual recorded trace by a smooth curve is much reduced or absent in lake-level records owing to a virtual lack of "sawtooth" fluctuations in the trace, apparently the result of better damping of short period waves.

In an effort to obtain some concept of the magnitude of the secondary sampling error caused by obtaining a mean lake level from hourly tabu-

lations of the gage record rather than from the continuous curve itself, a comparison was made between a monthly mean lake level as published by the U. S. Lake Survey and a monthly mean level computed from the continuous curve of the same gage record.

The lake-level gage record from Toledo, Ohio, for September, 1959, was used for the comparison. The area under the continuous curve, which was measured with a planimeter, was divided by the length of the base line in order to obtain the mean altitude of the lake surface curve above the bottom line of the gage record. The mean altitude of the curve was converted to feet (1.618 feet) and added to the mean elevation of the bottom line of the gage record of 570.512 feet (obtained from staff gage readings). This resulted in a mean elevation of 570.131 feet for the lake level—the mean elevation for September, 1959, published by the U. S. Lake Survey was 570.13 feet.

Despite the fact that only one comparison of one gage was made for one month of one year, the close agreement of the two means suggests that the secondary sampling error for monthly means is small.

## MEASUREMENT AND ERRORS

A review of the literature concerning the results of water-level gaging and the determination of rates of land uplift reveals that often the distinction between precise measurements and accurate measurements is not made, that statistical results are offered as proof of a statement without other supporting evidence, and that the Method of Least

Squares has been used without the prior removal of constant and systematic errors. These points suggest the need of a brief discussion of measurement and the influence of errors.

Measurement has been defined by N. R. Campbell (1957, pp. 267, 524) as, "... the process of assigning numbers to represent qualities," and "the primary object of measurement is to find a way of assigning to each of an ordered series of magnitudes a numeral, so that to each magnitude is assigned one and only one number and so that the order of the numerals is the order of the magnitudes...."

Numbers are assigned "by comparing systems with the standard series." Each "system" has a hypothetical true magnitude which is related to the true magnitudes of other "systems" by a numerical law (equation of condition) which is capable of being represented by an analytic function.

If measurements are carried out with the most accurate instruments available, where "... by the most accurate 'instrument' is meant, not merely a piece of apparatus which would ordinarily be called an instrument, but any arrangement whatever which permits measurement" (Campbell, 1957, p. 517), and with no discernable error of method, the observed magnitude may fail to approach the true magnitude by a maximum error E which is characteristic of the instrument of measurement and is dependent upon the smallest "step" of the instrument.

When measurements are carried out with the above qualifications it will be found that a series of measurements will fail to agree within

fixed limits. The range of the inconsistency is determined by the error of consistency which N. R. Campbell (1957, p. 475) defines as:

> Nothing but errors of method magnified until they can be directly detected by experiment. The magnification is effected through the equation of condition, and results either from the addition of several partial errors of method, each of which could not be detected separately, or from the transference of the error from a magnitude less accurately measurable to one which is more accurately measurable.

Campbell (1957, p. 509) states further that:

> The fundamental fact in the whole theory of errors of inconsistency [consistency] is that the true value of a complete collection of inconsistent measurements on a single magnitude is the arithmetic mean. If the collection (still consisting of measurements on a single magnitude) is incomplete, then we cannot determine the true value, that is really all that there is to be said about it. It may be convenient for some strictly limited purpose to express the results by a single numeral, and, if that is so, we shall probably select again the arithmetic mean as that numeral; but it cannot be too strongly insisted that the selection of that numeral does not imply a belief that it is the true value.

Measurements are usually divided into two general classes; (a) direct measurements which are made by observing the comparison of a standard with the system being measured, and (b) indirect measurements which are obtained by computation from direct measurements. It is apparent that the errors which affect indirect measurements are functions of the component direct measurements.

Errors are usually classified as: (a) gross errors ("blunders," "mistakes"), (b) constant errors which have the same effect (maintain the same sign and magnitude) on all the observations of a particular series of observations, (c) systematic errors whose algebraic sign and

magnitude are determined by a fixed relation to some condition (being based on a law, they may be detected if the law and its coefficients are known), and (d) accidental ("erratic," "residual," "experimental") errors which are the errors that remain after the gross, constant and systematic errors have been removed from the observation. Accidental errors are independent errors which are small in magnitude, are as likely to be positive as negative, and are much more likely to be small than large. Accidental errors are the only errors amenable to adjustment by the Method of Least Squares (Holman, 1904, pp. 4-10; Wright and Hayford, 1906, pp. 7-8, 45, 83, 273-278; Goodwin, 1920, pp. 7-12; Blunt, 1931, pp. 1-5; Beers, 1953, pp. 3-7; Anderson, 1955, p. 7; Rainsford, 1957, pp. 1-5).

The customary classification of errors in the preceding paragraphs would be encompassed by "errors of method" [if errors of method are considered to include the magnified errors of method (errors of consistency) in N. R. Campbell's (1957, pp. 267-294, 437-521) theory of measurement and error]. If errors of method exist in the observed magnitude the numerical law which relates that magnitude to other magnitudes cannot be determined; as long as these errors exist, the true magnitude, as represented by the arithmetic mean, cannot be found. When the errors of method are removed to the point that only errors of consistency remain, the arithmetic mean may be used as the true value and possible laws may be formulated which relate the magnitude to other systems.

The concepts of accurate measurement and precise measurement are also clarified by Campbell's theory. An accurate measurement is one in which both the errors of method and errors of consistency are insignificant; thus the observed value will approach the true value and may be related by numerical law to other magnitudes. Precise measurement, on the other hand, is measurement in which the errors of consistency are low but errors of method remain. In this situation several different series of determinations would yield similar magnitudes, but the equation of condition would be false and the magnitudes would not have the proper relation to other magnitudes. Because the goal of measurement is the determination of numerical laws, the taking of precise measurements (in that it reduces the error of consistency) is only a step in the determination of accurate values and is not an end in itself.

The Method of Least Squares which is:

> A mathematical method for determining: (a) the most probable value of a single quantity from a number of measurements of that quantity; (b) the probable error of the mean value of a number of observations; (c) the best curve which may be drawn for a series of observed values of the ordinate over a range of values of the abcessa (AGI, 1957, p. 184).

> ... rests upon the mathematical demonstration that where each of a very large number of observations of any quantity is of the same quality as the others, the most probable value of the quantity is the one for which the sum of the squares of the <u>residual</u> <u>errors</u> (or <u>corrections</u>) is a minimum...(Mitchell, 1948, p. 44).

The method has been a useful statistical tool for many years, and when used correctly provides the most probable values for observations. However, the fundamental requirement that first constant and systematic

errors be removed from the observations is, at times, not followed; thus erroneous conclusions are reached.

The importance of this requirement is emphasized by the following quotations:

T. W. Wright and J. F. Hayford (1906, p. 278) declared that:

> The detection of systematic or constant errors necessarily involves least squares as a basis, but this must be supplemented by something else, as the method of least squares deals with accidental errors only.

D. Brunt (1931, p.v.) states that:

> It cannot be too strongly insisted upon that the methods of Least Squares cannot in any way improve upon the actual observations. The application of these methods to a large number of carelessly conducted experiments cannot in general be expected to yield results as reliable as could be obtained from two or three carefully conducted experiments....

W. E. Deming (1943, p. 2) states:

> The principle of Least Squares provides a method for getting an adjusted value. It can be applied whether or not the data are worth adjusting, but the results are useful only when the data are good in the first place; no purely mathematical procedure can make a good figure out of any number of bad ones. Data not in statistical control—i.e., not random, are not usefully adjusted. It is important to know when data are worth adjusting.

and he continues (pp. 11-12) by declaring:

> The method of least squares can be applied to a single set of data, but no matter how carefully the least squares adjustment is carried out, the curve so fitted, or the observations so adjusted, do not have scientific validity unless there is other evidence at hand to show under what conditions the same or similar results will be obtained, and how these conditions are to be brought about and controlled.

The preceding discussion of errors and measurement has been made for three principal reasons:

(a) To point out that measurement is fundamentally the determination of numerical laws which relate true magnitudes to each other, and that it is necessary to approach the true magnitude as closely as possible (make accurate measurements) if these laws are to be discovered. For example, when we determine rates of postglacial uplift by means of water-level gages, we are trying to find the numerical law which relates the gage readings or difference in gage readings to the magnitude of the uplift; if the true relationship between the two quantities is to be found, it is necessary to recognize and remove the errors which exist in the measurements. The rates of uplift are valid only to the degree that the errors are removed or compensated for.

(b) To indicate the types of error which affect measurements and to bring out the fact that observations can be adjusted only after constant and systematic errors have been removed so that only accidental errors remain.

(c) To emphasize the fact that the application of statistical tools, such as the method of least squares, cannot be used to produce valid results unless the assumptions upon which the determination is based are true.

## PRECISE LEVELING

Precise leveling (also called "leveling of high precision,"

"precision leveling" and "first-order leveling") is the determination of elevations of sequential points on the earth's surface (bench marks) with respect to each other and to a datum plane by means of a refined leveling instrument with a very sensitive spirit level to indicate the horizon. Careful methods of taking and processing the observed elevations, together with a number of corrections (i.e., index, level, rod length, rod temperature, orthometric, curvature, and refraction corrections) reduce the magnitude of errors to certain prescribed limits and permit the establishment of accurate elevations.

Three international meetings held in 1867, 1912 and 1936 set the limits of error which would be allowed for each class of leveling. The 1867 meeting defined precise leveling as leveling with an average probable error not in excess of 3 millimeters per kilometer and a maximum probable error of not more than 5 millimeters per kilometer.

The meeting in 1912 prescribed the following classification (Rappleye, 1948b, p. 150):

> Therefore the Seventh General Conference of the International Geodetic Association, still preserving unchanged the limits of error of 1867 for precise leveling, decides to place hereafter in a new class of leveling, to be termed "leveling of high precision," every line, set of lines, or net which is run twice in opposite directions on different dates as far as possible, and whose errors, accidental and systematic, computed by the formulas hereinafter given, do not exceed—
>
> $\pm$ 1 mm per km for the probable accidental error,
>
> or
>
> $\pm$ 1.5 mm per km for the mean accidental error;

± 0.2 mm per km for the probable systematic error,

or

± 0.3 mm per km for the mean systematic error.

The Sixth General Assembly of the International Association of Geodesy issued new information as to the design of instruments and rods, methods of operation, computation and adjustments which were to be used for leveling of high precision. The Association also redefined leveling of high precision as a method of leveling with a total probable error not exceeding 2 millimeters per kilometer—leveling with a total probable error exceeding 2 millimeters but not exceeding 6 millimeters per kilometer was classified as "precise leveling" (Rappleye, 1948b, p. 154).

First-order leveling of the U. S. Coast and Geodetic Survey and the U. S. Lake Survey includes leveling in which the level lines are divided into 1 to 2 kilometer sections and the results of a forward and backward leveling over a section does not differ by more than 4.0 millimeters times the square root of the length of the section in kilometers (4.0 mm $\sqrt{K}$), or its equivalent: 0.017 times the square root of the length of the section in miles (Mitchell, 1948, pp. 45-46).

H. S. Rappleye (1948a, pp. 1-2) states:

> First-order leveling by the United States Coast and Geodetic Survey began with the transcontinental line of levels in 1878. Previous to that time the Bureau had done some leveling, but it was used mostly to control trigonometric leveling and, while it served its purpose, it was not of a high grade of accuracy compared with the standards of today....

and

> The first-order leveling done by the United States Coast and Geodetic Survey since 1899 falls within the limits prescribed

for "leveling of high precision" at the Hamburg meeting [1912]. In the 1912 adjustment of the first-order level net the average probable accidental error per kilometer was plus or minus 0.71 millimeter and the average probable systematic error was plus or minus 0.08 millimeter.

## Finnish Uplift Rates By Precise Leveling

Finland presents an almost ideal situation for the determination of extensive non-volcanic land uplift by precise leveling. Finland's borders are from c 67 miles (108 km) to c 355 miles (574 km) to the southeast of the former Fennoscandian ice center; thus Finland is very close to the region of maximum uplift.

The underlying igneous and metamorphic bedrock crops out in many areas which allows the placement of numerous bench marks in the stable bedrock; thereby reducing the errors due to shifting bench marks. Probably the most important factor, other than proper instruments and techniques, in the determination of accurate absolute rates of uplift is the fact that the level net is tied into either 14 primary tide gages (first precise leveling) or 12 tide gages (second precise leveling).

The average distance between the 14 tide gages, measured along the leveling lines, was c 78 miles (126 km); the shortest distance was c 36 miles (58 km); and the longest distance was c 138 miles (222 km). The distances between the 12 tide gages of the second precise leveling were: (a) average distance c 81 miles (130 km), (b) shortest distance c 55 miles (88 km), and (c) the longest distance c 138 miles (245 km). The point on the level line polygon which is farthest from a tide gage is c

197 miles (317 km) from the gage, and the point on a level line common to both precise levelings which is farthest from a tide gage is c 182 miles (293 km) from that gage.

The information in the following paragraphs regarding the Finnish precise levelings of 1892-1910 and 1935-1955 is from E. Kääriäinen's "On the Recent Uplift of the Earth's Crust in Finland" (1953, pp. 31-64).

The leveling net of the First Precise Leveling consisted of 11 closed polygons with a total length of leveling lines in the principal net of 2464 miles (3967 km). The smallest polygon was 71.4 miles (115 km) in length and the others ranged from 142.2 miles (229 km) to 502 miles (808 km) in length. Approximately 3,000 bench marks were placed in bed-rock, "immovable" boulders and stone foundations at spacings of 0.93-1.24 miles (1.5-2 km).

"From the closing errors of the polygons, the greatest of which was 66.30 mm it was computed that the mean error of the levelings was ± 1.23 mm/km" (1953, p. 34).

The Second Precise Leveling consists of a network of 13 closed polygons with circumferences ranging from 146 miles (235 km) to 543 miles (874 km). After World War II, 2843 miles (4577 km) of leveling lines and 12 tide gage stations remained within Finnish territory.

"... The greatest closing error, without taking into account the refraction and the land uplift correction is 22.10 mm. The mean error of the Second Leveling, as computed from closing errors, is ± 0.45 mm/km" (1953, p. 36).

The leveling lines common to both the First and Second Leveling totaled 2309 miles (3717 km). Although about 70 per cent of the old bench marks were found (c 46 per cent of which were on rock), the land uplift calculations were based almost entirely upon 900 highly dependable rock bench marks; in a few cases bench marks on boulders were used.

After the necessary computation, corrections and adjustments were made to the leveling lines and nets, the mean errors of the yearly land uplift values were calculated for 28 tie-points, and a value of "... ± 0.3 mm as the average mean error of the yearly land uplift obtained by precise leveling" (1953, p. 59) was computed. The rates of uplift of the 12 tide gage stations are listed on page 93 of this paper.

Great Lakes Region—Precise Leveling

Elevations on the Great Lakes have been determined since the first complete leveling in 1875 by a combination of spirit-level measurements and water-level measurements. U. S. Lake Survey leveling lines have originated at a bench mark in Rensselaer, New York, called Greenbush Gristmill (see Appendix I). The elevation of Greenbush Gristmill above sea level was determined by the U. S. Coast and Geodetic Survey in 1856-57, 1877, 1894, 1902, 1934, and 1955. Instrumental level lines are run between Greenbush and Oswego, New York (the first point of elevation on the Great Lakes proper, and between each of the other Great Lakes. Water-level determinations are used to carry the elevations from the eastern to the western ends of the lakes (Comstock, 1882, pp. 595-609).

The geographic factors inherent in the location of the leveling lines used to determine rates of land uplift in the Great Lakes Region are in distinct contrast to the favorable situation which exists in Finland.

Elevations in the Great Lakes Region are based on leveling lines run forward and backward from the tide gage at New York City to the Greenbush Gristmill bench mark, a distance of c 147 miles (237 km); the level lines are then continued by another organization to Oswego, New York, on Lake Ontario, a distance of 173-195 miles (278-314 km) depending upon the route taken.

From Oswego, the elevations are carried by alternating water-leveling and spirit leveling a distance of c 1212 miles (1950 km) to Duluth, Minnesota. If the rates of uplift are to be calculated for the Lake Superior area, elevations for Port Arthur, Ontario, are used. Port Arthur (which is c 185 miles [298 km] from Duluth) elevations were determined by yet another organization, the Canadian Hydrographic Service, from a comparison with lake-level gage records at Marquette, Michigan, from 1907-1914.

The total length of the leveling lines, both water-level and spirit level, from the tide gage at New York City to the farthest point in the level net (Port Arthur) is approximately 1720 miles (2768 km). This situation is to be compared with the Finnish leveling lines suitable for determining rates of uplift which total 2309 miles (3716 km) and are tied into 12 tide gages. The point which is farthest from a tide gage in

the Finnish level net common to the First and Second Levelings is c 182 miles (292 km) from the tide gage.

The tide gage records used in the Finnish level nets are corrected for the eustatic rise of sea level, meteorological effects, and instrument and operator error, as well as for astronomical tides. The tide gage record at New York City on the other hand, is of a sufficiently long period to eliminate the majority of the astronomical tides and meteorological effects, but the other influences remain uncorrected. Elevations from lake-level gages records are uncorrected observed elevations of the lake surface.

A final comparison between the two areas may be made on the basis of the distances of the areas of uplift from their respective Pleistocene ice centers. The Finnish tide gage at Leppäluoto, which is c 83 miles (134 km) from the ice center, undergoes an uplift of 2.69 feet/100 years (8.80 ± 0.33 mm/year), and the tide gage at Hamina, 346 miles (557 km) from the ice center, is uplifted at a rate of 0.82 foot/100 years (2.70 ± 0.24 mm/year). The distances of these gages from the ice center are to be compared with the distances from the Laurentian ice center to points in the Great Lakes region. For example, the distance from the Canadian ice center to Oswego, New York is c 800 miles (1288 km); from the ice center to Duluth, Minnesota, is c 870 miles (1400 km); and from the ice center to Milwaukee, Wisconsin, on Lake Michigan the distance is c 1110 miles (1790 km).

A concise summary of the caution needed in using precise leveling to

detect rates of crustal movement is stated by F. Németh (1960, p. 53), who declared:

> Geodesists have long drawn attention to the fact that leveling data should be used as evidence of crustal movement only with caution. The differences in altitude of leveling sections are mostly reliable only to the order of a millimeter because of measurement error; however, movements of ground and structure can multiply the measurement error. A difference in compared altitude values can also stem from adjustment of different leveling networks. For investigation of changes of level, only one and the same network specially stabilized for this purpose and always measured by the same methods is suitable.

FENNOSCANDIAN—GREAT LAKES ANALOGY

Numerous comparisons have been made of the postglacial land uplift of Fennoscandia and the Great Lakes Region (e.g., De Geer, 1892; Gutenberg, 1933, 1941, 1954; Flint, 1957) which stressed the over-all similarity of uplift in the two areas but did not compare in detail the relationships between maximum depressions, distances from their respective ice centers, and the rates of modern uplift.

If the two regions are analogous, it would seem that an examination of the rate and extent of modern land uplift in Fennoscandia would aid in locating, at least approximately, the zero isobase of modern land uplift in the region which had been covered by the Laurentide ice sheet. Although the Fennoscandian ice sheet was smaller than the Laurentide sheet, both areas had approximately the same thickness of ice, 10,000+ feet (2,500+ meters), and consequently about the same depth of depression of the crust. Therefore the distance from the ice center to the zero

isobase in the Great Lakes-Hudson Bay area should be roughly equal to the distance from the Fennoscandian ice center to the zero isobase at Leningrad, U.S.S.R.

The Fennoscandian uplift values in Table 2-A are from Kääriäinen (1953, p. 59, Fig. 4); distances were measured from the location of the axis of maximum ice thickness in eastern Sweden (Flint, 1957, p. 368, Plate 5) to each of the twelve tide gages. The distances from the Laurentide ice divide to points in the Great Lakes-Hudson Bay region (Table 2-B) were determined from the Glacial Map of Canada (Geological Association of Canada, 1958).

A plot of the uplift of the Finnish tide gage stations, determined by precise leveling (in feet per 100 years), against their distances (in miles) from the Fennoscandian axis of maximum ice thickness reveals that the distribution of points lies almost in a straight line—the slope of the line fitted by the method of least squares gives a modern rate of uplift of 3.36 feet/450 miles/100 years or 0.75 foot/100 miles/100 years. This rate of 0.75 foot/100 miles/100 years might then be assumed to be of the proper order of magnitude for the modern Laurentide land uplift.

If the analogy with Fennoscandia holds, the zero isobase of the land uplift would follow along a line extending down from the western fifth of Hudson Bay to the southwestern shore of James Bay (just southwest of Moosoonee, Ontario) then to the vicinity of Kempt Lake, Quebec, crossing the St. Lawrence River about 20 miles northeast of Quebec, Quebec. The relationship of Churchill, Manitoba, to the zero isobase, i.e., Churchill

TABLE 2-A

FENNOSCANDIAN UPLIFT RATES AND DISTANCES

| Finnish Tide Gages | Distance from Axis of Maximum Ice Thickness | | Yearly Uplift in mm and Mean Error By Precise Leveling | Uplift in Feet/100 Years |
|---|---|---|---|---|
| | Kilometers | Miles | | |
| 1. Leppäluoto | 134 | 83 | 8.80 ± 0.33 | 2.69 |
| 2. Vaskiluoto | 141 | 87 | 8.77 ± 0.30 | 2.68 |
| 3. Horankallio | 146 | 91 | 9.02 ± 0.43 | 2.75 |
| 4. Kaskinen | 184 | 114 | 7.66 ± 0.32 | 2.34 |
| 5. Kemi | 190 | 118 | 8.52 ± 0.53 | 2.60 |
| 6. Toppila | 196 | 122 | 8.25 ± 0.43 | 2.52 |
| 7. Mäntyluoto | 258 | 160 | 6.96 ± 0.25 | 2.12 |
| 8. Rauma | 296 | 184 | 6.82 ± 0.28 | 2.08 |
| 9. Ruissalo | 383 | 238 | 5.30 ± 0.28 | 1.62 |
| 10. Hanko | 460 | 286 | 3.58 ± 0.35 | 1.09 |
| 11. Helsinki | 503 | 312 | 2.90 ± 0.25 | 0.88 |
| 12. Hamina | 557 | 346 | 2.70 ± 0.24 | 0.82 |
| Leningrad, USSR | 717 | 446 | 0.00 | 0.00 |

TABLE 2-B

DISTANCES FROM THE LAURENTIDE ICE DIVIDE

| | Approximate Distance from Ice Divide | |
|---|---|---|
| | Kilometers | Miles |
| 1. Father Point, Quebec | 645 | 400 |
| 2. James Bay (Moosoonee [Collis]), Ont. | 750 | 490 |
| 3. Kempt Lake Quebec | 805 | 500 |
| 4. Ottawa, Ontario | 1040 | 645 |
| 5. Churchill, Manitoba | 1060 | 660 |
| 6. Lake Ontario (Kingston, Ontario) | 1210 | 750 |
| 7. Lake Huron (Manitoulin Island, Ontario) | 1255 | 780 |
| 8. Lake Michigan-Huron (Mackinaw City, Mich.) | 1380 | 855 |
| 9. Lake Superior (Duluth, Minnesota) | 1400 | 870 |
| 10. Lake Erie (Buffalo, New York) | 1430 | 885 |
| 11. Lake Michigan (Milwaukee, Wisconsin) | 1790 | 1110 |

is c 100 miles farther away from the ice center than the presumed zero isobase, may support those investigators who deny the existence of land uplift at Churchill (Tyrrell, 1896; Johnson, 1939; Cooke, 1942; Williams, 1949) as opposed to those who claim that up to c 2 meters (6.6 ft) of uplift per century is taking place at Churchill (Bell, 1897; Gutenberg, 1941, 1942, 1954).

It is possible that the ice which covered Churchill came from the ice divide to the west of Hudson Bay; if this were the case, Churchill, being about 285 miles from the western ice divide, would have a modern land uplift of about one foot per century (again applying the modern Fennoscandian rate of uplift).

The tide gage at Father Point, Quebec (being about 400 miles from the Laurentide ice divide), is located within the proposed area of uplift and could be undergoing an uplift of c 0.37 ft/100 years (based on the modern Fennoscandia rate). The importance of uplift at Father Point, Quebec, lies in the fact that it is one of the tidal bench marks upon which the Canadian precise level net is based; furthermore it is the starting point for the determination of the new International Datum for the Great Lakes.

The advisability of using the tide gage at Father Point may be questioned for three reasons:

(a) The gage is located within the area of postglacial uplift. If uplift is now occurring, and if corrections are not made for the uplift, precise levelings taken a number of decades apart would show an

apparent subsidence of the land;

(b) the gage is situated near the small end of a "funnel" formed by the Gulf of St. Lawrence, the estuary of the St. Lawrence River and the St. Lawrence River. The convergence of the shorelines greatly increases the influence of meteorological effects (see pp. 58-59, 73-75), which in turn makes difficult the determination of an accurate mean sea level; and

(c) the Father Point tide gage is on the eastern side of an ancient fault zone (Logan's Line), whereas the greater part of the Canadian level net and the whole of the Great Lakes region lies to the west of the fault zone. Although the fault zone is an ancient one, it would be prudent not to have the key tide gage of a leveling net and the greater part of the net on opposite sides of a fault zone.

The modern zero isobase of postglacial land uplift cannot be in the known area of horizontality (i.e., south west of the Nipissing zero isobase). Moreover if the modern zero isobase were in the vicinity of the southwestern shore of James Bay; then, as is indicated in Table 2-B and Plate I, the postglacial uplift would take place northeast of a line which passes near the southwestern shore of James Bay and which curves eastward so as to cross the St. Lawrence River just north of Quebec, Quebec. Under these circumstances, the maximum possible southern extent of postglacial crustal movement would include almost all of Lake Superior, less than the northern one-fourth of Lake Michigan, less than the

northern two-thirds of Lake Huron and less than the northern three-fourths of Lake Ontario. The minimum extent of the southern boundary of uplift on the other hand would be somewhere near James Bay—which would mean that modern land uplift in the Great Lakes region would be nonexistent. The actual southern limit of uplift should lie somewhere between these two extremes—probably closer to the Great Lakes than to James Bay.

## IV. PREVIOUS DETERMINATIONS OF RATES OF UPLIFT

Rates of uplift in the Great Lakes region have been computed by various investigators who used Gilbert's method of calculation based on the principle of "water leveling" (see pp. 7-11, 40, 68-69). Examples of the magnitude of uplift in the Great Lakes are given in Table 3, which also indicates the direction of uplift between the gages of each pair of gages. The land is uplifted in a direction extending from the geographic location of the first gage of the pair toward the second gage.

The directions of uplift in Table 4 were found by projecting the isobases of former glacial lake shoreline features through the locations of the gages; the gage of a particular pair which was on the higher isobase was considered to be the gage which was "upslope." Thus the directions of land uplift in Table 4 are based on uplift which warped former shorelines, whereas the directions in Table 3 represent modern uplift calculated from lake-level gage records.

If the directions of uplift between the pairs of gages in Table 3 are compared with the directions of uplift between the same pairs of gages in Table 4, it will be found that the direction of uplift will be reversed for certain pairs of gages, e.g., Marquette-Duluth, Conneaut-Cleveland, Oswego-Charlotte, etc. In cases of discrepancy the directions, and therefore the rates, in Table 3 must be incorrect.

TABLE 3

EXAMPLES OF PREVIOUS DETERMINATIONS OF RATES OF UPLIFT IN FEET/100 MILES/100 YEARS

| After | Lake Superior | | Lake Mich.-Huron | | Lake Erie | | Lake Ontario | |
|---|---|---|---|---|---|---|---|---|
| | Max | Min | Max | Min | Max | Min | Max | Min |
| Gilbert (1896-97, p. 636) | -- | -- | 0.43[a] | 0.39[b] | 0.46[c] | -- | 0.37[d] | -- |
| Moore (1922, pp. 154, 181) | 0.27[e] | 0.26[f] | 0.27[a] | 0.24[g] | 1.04[h] | 0.38[i] | 0.74[j] | 0.32[k] |
| Gutenberg (1933, p. 457) | 0.84[l] | 0.12[m] | 1.08[n] | 0.01[o] | 0.83[h] | 0.36[i] | 6.63[p] | 0.28[q] |
| Gutenberg (1941, p. 742) | 0.61[l] | 0.03[m] | 0.48[r] | 0.09[s] | 0.55[t] | 0.0 | 1.34[p] | 0.06[v] |
| Moore (1948, p. 700-701) | 0.44[w] | 0.07[x] | 0.35[r] | 0.07[o] | 0.34[y] | 0.09[u] | 0.57[z] | 0.13[aa] |

Land is uplifted in the direction of the second gage site.

a. Milwaukee-Port Austin
b. Milwaukee-Escanaba
c. Cleveland-Port Colborne
d. Charlotte-Sacketts Harbor
e. Marquette-Sault Ste. Marie
f. Marquette-Duluth
g. Milwaukee-Harbor Beach
h. Cleveland-Amherstberg
i. Cleveland-Buffalo
j. Oswego-Charlotte
k. Oswego-Toronto
l. Duluth-Port Arthur
m. Michipicoten-Port Arthur
n. Calumet Harbor-Milwaukee
o. Harbor Beach-Escanaba
p. Kingston-Cape Vincent
q. Port Dalhousie-Kingston
r. Harbor Beach-Collingwood
s. Calumet Harbor-Harbor Beach
t. Port Stanley-Port Colborne
u. Cleveland-Port Stanley
v. Kingston-Oswego
w. Marquette-Port Arthur
x. Marquette-Houghton
y. Conneaut-Cleveland
z. Port Dalhousie-Oswego
aa. Oswego-Cape Vincent

TABLE 4

POSSIBLE DIRECTION OF UPLIFT BETWEEN GAGE SITES AS INFERRED FROM RELATIONSHIP TO ISOBASES OF FORMER GLACIAL LAKE FEATURES

| | | |
|---|---|---|
| | Lake Superior | |
| Duluth-Marquette | Port Arthur-Michipicoten | Marquette-Port Arthur |
| Duluth-Port Arthur | Marquette-Sault Ste. Marie | Marquette-Michipicoten |
| Duluth-Michipicoten | Marquette-Houghton | |
| | Lake Michigan-Huron | |
| Milwaukee-Port Austin | Calumet Harbor-Harbor Beach | Harbor Beach-Escanaba |
| Milwaukee-Harbor Beach | Grand Haven-Harbor Beach | Harbor Beach-Goderich |
| Milwaukee-Escanaba | Sturgeon Bay-Harbor Beach | Harbor Beach-Calcite |
| Milwaukee-Bay City | Harbor Beach-Collingwood | |
| Calumet Harbor-Milwaukee | Harbor Beach-Mackinaw City | |
| | Lake Erie | |
| Cleveland-Port Colborne | Cleveland-Port Stanley | Toledo-Cleveland |
| Cleveland-Buffalo | Cleveland-Erie | Port Stanley-Port Colborne |
| Cleveland-Amherstburg | Cleveland-Conneaut | Port Colborne-Buffalo |
| | Lake Ontario | |
| Charlotte-Sacketts Harbor | Kingston-Cape Vincent (zero uplift-same isobase) | Toronto-Oswego |
| Charlotte-Oswego | Port Dalhousie-Oswego | Toronto-Kingston |
| Fort Niagara-Oswego | Port Dalhousie-Kingston | Toronto-Cape Vincent |
| Olcott-Oswego | Port Dalhousie-Toronto | |
| Oswego-Kingston | | |

Note: Land is uplifted in the direction of the second gage site, i.e., uplifted to the northeast.

## Earlier Discussions Of Errors

As has been stated previously, the fundamental assumption which underlies water-leveling and the determination of Great Lakes rates of uplift is that the summer season mean lake surface is level and may be used as a plane of reference. The importance of this concept must be stressed, for obviously if the mean lake surfaces are not level during the summer months, comparisons cannot be made between the gage differences of two gages over a period of time due to the lack of a standard reference point. If gages are compared by means of a lake surface which is not level, then the rates of uplift which result from the comparison are not valid.

### GILBERT'S INITIAL STUDY (1896-97)

The problem of determining a level lake surface, as well as the effects of the various other factors which influence the taking of accurate water-level measurements, was completely understood by G. K. Gilbert who made the first computation of modern rates of crustal movement in the Great Lakes. His understanding of the types of errors involved, their importance, and the means of avoiding or eliminating them was not approached by subsequent investigators. The following quotation is taken from Gilbert's (1896-97, pp. 641-645) chapter "Plans For Precise Measurement"— plans which, if they had been followed and developed, would have largely eliminated the various types of error which prevent the accurate measurement of water-level elevations.

Gilbert (pp. 643-644) explained that:

In bays and estuaries there are local temporary variations occasioned by the floods of tributary streams.

There are solar and lunar tides, small as compared to those of the ocean, but not so small that they may be neglected.

The wind pushes the lake water before it, piling it up on lee shores and lowering the level on weather shores. During great storms these changes have a magnitude of several feet, and the effect of light wind is distinctly appreciable. Even the land and sea breezes, set up near the shore by contrasts of surface temperature, have been found to produce measurable effects on the water level.

There is also an influence from atmospheric pressure. When the air is in equilibrium, if that ever occurs, the pressure is the same on all parts of the lake surface, and the equilibrium of the lake is not disturbed; but when the air pressure varies from point to point this variation of pressure is a factor in the equilibrium of the water surface, the surface being comparatively depressed where the air pressure is greater and elevated where it is less.

When a storm wind ceases, the water not merely flows back to its normal position but is carried by momentum beyond, and an oscillation is thus set up which continues for an indefinite period. A similar oscillation is started whenever the equilibrium is disturbed by differences of atmospheric pressure; and these swaying motions, called seiches, ..., persist for long periods. In fact, they bridge over the intervals from impulse to impulse, so that the water of the Great Lakes never comes to rest.

..........................................................

These various influences work independently but simultaneously, and their effects are blended in the actual oscillations of the water surface at any point. In using the water surface for the purpose of precise leveling, it is necessary to take account of all such factors and make provision for the avoidance or correction of the errors they tend to produce.

..........................................................

The gage employed for the determination of water height should be of some automatic type, giving a continuous record. This is necessary in order that the study of the record may furnish data for the complete elimination of errors from tides, seiches, and land and sea breezes. ... It should be installed as to be secure from settling. The height of its zero should be readily verifiable.

Near each station there should be at least three benches, constructed with special reference to permanence and stability.

> They should be independent of one another and independent of other structures.
>
> Pressure of the air should be continuously recorded by a baragraph, carefully standardized. A wind vane and anemometer should give automatic records.

Although Gilbert realized the importance of the factors which affect the determination of rates of uplift, he was limited, as in any pioneer study, by the data available. Gilbert attempted to avoid the effect of wind slope by using only those records which were taken on days of very light wind; he was no doubt unaware of the fact that wind-drift currents (hence the piling up of water) are the result of the effects of wind stresses which were applied up to 10-12 days before the day of measurement (Millar, 1952, pp. 336-337; Ayers, et al., 1958, pp. 112-115; Ayers, 1959, pp. 4-5).

Gilbert (pp. 637-638) discussed the other sources of errors as follows:

> The probable errors of the individual measurements are rather high, ranging from 14 to 50 per cent, and this suggests the possibility that the closeness of their correspondence may be accidental. It should be remembered also that at two or three stations there was reason to believe that the gage zeros were settling during the period in which the observations were made, and the results involve the doubtful assumption that the rate of settling was uniform. There is room for doubt as to the precision of the instrumental leveling; in only a few instances is the fact of duplicate measurements recorded, and single measurements are notoriously insecure. Error was doubtless admitted by ignoring the effects of barometric gradient. River floods may have introduced errors. ... There may also be personal equations of observers, especially as the gages at pairs of stations were not in every case of the same type. For all these reasons I am disposed to ascribe only a low order of precision to the deduced rate of change, and regard it as indicating the order of magnitude rather than the actual magnitude of the differential movement.

"LEVEL" LAKE SURFACES

The validity of the assumption that the Great Lakes water surfaces are level during the summer was questioned in 1897 by William T. Blunt, engineer of the U. S. Deep Waterways Commission, in "Effects of Gales on Lake Erie" (Blunt, 1897, pp. 155-168).

Blunt (p. 156) declared:

> In the survey of the Northern and Northwestern Lakes the assumption was made that the mean surface of each lake was level within the limit of possible instrumental errors in traversing its length, and all heights and gauges west of Oswego have been based on this assumption. The actual period of observations used to transfer the level by lake surface was from May 11 to August 31, 1875; and while it is certain that the eminent officer then in charge of the survey took every precaution to obtain accurate results, it will still be a matter of scientific if not of practical interest to have a verification of these elevations. When we consider the marked effects of even light winds on the surface of Lake Erie, the very decided effects of strong continuous winds, and the extraordinary effects of gales, in connection with the fact that the great preponderance of winds is from the westward, the proposition that even the mean surface is level appears somewhat clouded; it at least requires verification.

John F. Hayford, geodesist and engineer, completed an investigation in 1922 which also refutes the assumption that summer mean lake surfaces are level; the results of the investigation were published by the Carnegie Institute of Washington in Publication 317, "Effects of Wind and of Barometric Pressure on the Great Lakes."

The principal problem of determining accurate lake-level elevations was stated by Hayford (p. 2), who declared:

> As the investigation progressed, it gradually became more clearly evident that the largest and most serious errors encountered were those which arise from the fact that the

> surface of any one of the Great Lakes at any given instant is not level except by accident. The surface has a slope at every point due to the influence of winds and barometric pressures.

Hayford, for the most part, dealt with the short-term departures from level; however his discussion of tide gage records indicates that he also realized the importance of the seasonal effect of wind and barometric pressure (the conclusions reached apply equally well to lake-level gages). Hayford (p. 132) pointed out that:

> It should not be overlooked in this connection that the prevailing winds and the prevailing barometric gradients tend to be seasonal, to be repeated each year, and that therefore the taking of a mean for several years is of only moderate effectiveness in reducing the error in the mean. The monthly values of mean sea-level at various tide gages support the statement by showing a seasonal variation, as a rule, and thereby incidentally indicating that the wind effects and barometric effects are certainly decidedly appreciable in the monthly means.

The final chapter of Hayford's book dealt with the "Application to Determination of Tilting of the Great Lakes Region." There Hayford (p. 133) said:

> The rate of tilting as derived was .0042 foot per mile per century—an exceedingly small rate of change. The conclusion was derived from apparent changes of relative elevation of the water surface as measured at different gages on Lakes Michigan-Huron, Erie, and Ontario in different years. The amounts of change involved are of the order of 0.1 to 0.2 foot in a period of 20 to 40 years. Evidently, when such small changes are in question there is more chance of securing the necessary accuracy if corrections as large as those shown in Tables Nos. 19 to 23, pages 80-96 of this publication, for barometric effect and wind effects, are taken into account. ...
>
> ..........................................................
>
> The deductions of Gilbert are probably correct in the main. But a new investigation based on observed elevations of water surface corrected for wind effect and barometric effects would have greater accuracy and is desirable.

Sherman Moore's first determination of rates of crustal movement in the Great Lakes region (examples of which are given in Table 3) was also published in 1922. In his first paper, "Tilt of the Earth in Great Lakes Region," Moore devoted several paragraphs to the errors which affect lake-level gage readings; this discussion of errors is in sharp contrast to his second paper published in 1948 which contained only two sentences referring to errors (one remark is on bench mark stability and the other suggests that scatter of points may be due to varying wind and barometric conditions).

One statement is particularly pertinent to the discussion of "level" lake surfaces. Moore (1922, p. 153-154) declared that:

> The lakes themselves are not always level. Prevailing winds and continued differences in barometric pressure cause tilting of the surface which may last for considerable periods of time. These inequalities will usually balance in a long period of time, but even a yearly mean is not free from their effects.

Apparently Moore did not realize that the second sentence of the quotation nullified the assumption—that the summer mean lake surface is level—upon which his method of determining uplift rates is based.

Beno Gutenberg's initial paper on "Tilting Due to Glacial Melting" (1933) contains only one reference (on bench mark stability) to errors in the treatment of Great Lakes rates of uplift. His second paper, published in 1941, discussed the influence of the following factors upon the recording of tide gage elevations: meteorological effects, eustatic changes, water and shore conditions, local movements, effects of the

method of observation, effects of errors, and land movement. His observations relating to the measurement of lake-level elevations on the other hand were scanty. Gutenberg (p. 740) said:

> Absolute values (corresponding to the column 6 in Table 4) were not calculated, as they are influenced by the general change in the lake level due to precipitation, flow in rivers, vertical movements of the region of the outlet, wind and other causes.

In addition, he (p. 745) said:

> Apparently, there are meteorological conditions which affect the mean lake level at the various stations on Lake Ontario more than those in the other lakes and therefore it is to be expected that the results for Lake Ontario are less accurate.

It may be seen from the foregoing paragraphs that the existence of factors which prevent a lake surface from being a level surface was known to those investigators who used the lake surface as a datum plane in the comparison of pairs of gages in their attempts to measure rates of crustal movement. However these investigators seemingly regarded the influence of meteorological effects, etc., as constituting only a temporary disturbance of level and therefore continued to use uncorrected lake surface elevations in their calculations.

## OTHER ERRORS

The existence of other types of error which affect the taking of lake-level elevations was known to those investigators who measured rates of crustal movement. This fact is demonstrated by the papers of Sherman Moore, engineer of the U. S. Lake Survey, who discussed the various types of errors in his first paper on rates of tilting (1922) and

in his gage histories (1939-44). The following quotations from Moore's 1922 paper point out the poor quality of the early measurements—measurements incorporated in the calculation of rates of uplift which, according to Moore (1922, p. 182), averaged 0.43 ± 0.07 foot/100 miles/100 years.

Moore (1922, pp. 153-155, 181) stated that:

> Practically, the determination is complicated by errors arising from several causes. Gage readings are frequently incorrect due to mistakes in reading the gage, but more frequently to failure to check the zero of the gage back to stable benchmarks sufficiently often. Benchmarks are not always stable, but are subject to local settlement. Benchmarks are frequently destroyed, and unless there is more than one benchmark at the point, later records are not comparable. ...
>
> ... From 1860 the records are complete at some points, but until about 1872 the gages, in the majority of cases, were poorly cared for, and were not properly referenced to fixed benchmarks. In the seventies more care was given to the gages, and levels connecting their zeros with fixed benchmarks were run at frequent intervals. Unfortunately the records of the actual gage readings are not available. Tabulations of lake levels referred to some plane of reference are in the published reports, but the elevations are frequently inconsistent, contain some gross errors, and as a whole they are not fully reliable. ... During the period 1880 to 1899, the gages apparently received but little care, and at points where there existed unstable conditions, the records have but little value. Since 1899 the gages have been well cared for, self-registering instruments have been installed, and frequent check levels have been run. The locations of many of the present gages are not the same as those of the earlier ones, and even where the location is the same it has been impossible in some cases to recover the old benchmarks.
>
> ...............................................................
>
> At Harbor Beach the records began in 1875. The records before 1900 are staff gage readings, and there is evidence that the gage was not well cared for. There were frequent changes in gages and benchmarks, but the majority of the benchmarks have been recovered and their elevations determined. The records as a whole are probably good, although considerable variation between individual years is noted.
>
> ...............................................................

For Lake Erie, the gage at Cleveland is standard. The record goes back to 1860, and although the history of the gage is at times obscure, the elevations are believed to be good. At Buffalo a self-registering gage has been maintained since 1899. The records before this time were staff readings made on various gages at different points in the harbor. No level connections between the earlier and the later work can be found.

... At Amherstburg there are records of a self-registering gage since 1899, but the observations scatter rather widely due probably to a variable fall in the river. ...

Oswego, at the present time, is accepted as the standard gage for Lake Ontario. Its history in the earlier years is somewhat obscure, but the elevations since 1860, have been accepted as correct. Until about 1880 Charlotte was considered the standard gage. Several attempts have been made to obtain something consistent out of the records at this point, but never with any success. ... The gages and reference points have always settled, although it is believed that the original benchmark on the lighthouse has been stable.

At Port Dalhousie, actual gage readings and direct levels to the benchmark are available for 1875, at the time of the transfer of precise levels. The records for earlier years are referred to depths over the lower sill of the lock, and to make them agree with other records on Lake Ontario it is necessary to assume changes in the elevation of the sill as great as two feet, which of course is impossible. ...

At Toronto there are records of the water surface elevation since 1860, made by the harbor master. It is believed that they are all referred to the same benchmark, and that the latter has been stable. However, various devices have been in use to indicate within the harbor-master's office, the stage of the lake, and these have usually been faulty. This has resulted in errors, which, due to failure to check the accuracy of the indicating mechanism have at times been carried through several years. As a result the observations scatter very badly, but a mean line is probably very near to the truth.

The gage records at Kingston fall into two groups, 1895-1901, and 1908-1919. The earlier records are depths over the invert of the dry dock, the elevation of which was determined by comparison with Tibbetts Point. The later group is referred to benchmarks the elevations of which were determined by another water level transfer. So far as is known there is no instrumental level connection between the two groups. The records of the self-registering gage at Tibbetts Point, maintained since 1901, scatter badly due to local conditions, and the determinations of a line through them is unsatisfactory. ...

ERRORS DUE TO GAGE LOCATION

Two types of gage locations are important in affecting the accuracy of lake-level gage readings, which in turn influences the accuracy of precise leveling and rates of uplift. The first type of location is the relation of the gage site to the local geography and underwater conditions, and the second type is the relation of the gage site to the area of horizontality of past uplift.

The effect of local topography and depth of water upon the height of the water surface has long been known (e.g., Humboldt, 1849, pp. 309, 310; Whittlesey, 1859, pp. 6, 8-10, 18, 24; Henry, 1902, p. 13; etc.), and the importance of gage site location with respect to the area of horizontality of former glacial lake shorelines was clearly explained by Frank B. Taylor (1927) in a paper to the Michigan Academy of Science Paper entitled "The Present and Recent Rate of Land-Tilting in the Region of the Great Lakes."

An example of the effect of gage location near a river is given by the monthly mean elevation sheets for Oswego, New York before 1932 (U. S. Lake Survey, n.d.) where a note at the bottom of the elevation sheet said:

> The records have been carefully kept and are reliable, but do not always indicate the stage of Lake Ontario, as the gage readings are influenced by high stages of water in Oswego River. These high stages usually occur in spring months, and give readings from 0.2 ft. to 0.3 ft., or even more, above the level of Lake Ontario.

The interconnecting ramifications of the effects of lake-level gage locations and their importance to precise leveling and accurate computation

of rates of uplift is very well brought out by the relationships of four gages on Lake Ontario.

Sherman Moore (1941, pp. 2-3) in his gage history of Tibbett's Point declared:

> 10. The gage record at Tibbett's Point is of but little value, due to local conditions which resulted in failure of the gage to give Lake Level. From the first, the gage was in the well from which water was drawn for the boilers in the fog signal station. The bottom to the southwest of the point is very flat and shallow, and to insure a supply of water in the well at low lake stages, a channel several hundred feet in length to deeper water was cut in the bottom. This was filled with large broken rock. With westerly winds, the seas running over the flat bottom and beach would hold the water in the well above lake level, and the gage would read too high.
>
> .............................................................
>
> 14. The elevations at Tibbett's Point here listed do not give true elevations of Lake Ontario within about 0.15 ft. The discrepancy is a function of the direction and velocity of the wind.

The significance of the above quotation may be seen when its conclusions are compared to the following material from the gage histories of the Canadian Hydrographic Service (n.d.):

> Elevations at Kingston on 1903 Datum are based on a comparison of float gage readings for 1909 and 1911 to 1915, with water surface elevations at Tibbett's Point. ...
>
> Elevations at Toronto on 1903 Datum are based on comparisons of float gauge readings from 1907 to 1909 with water surface elevations at Tibbett's Point and from 1917 to 1925 with water surface elevations at Kingston.
>
> Elevations at Port Dalhousie on 1903 Datum are based on a comparison of float gauge readings from 1914 to 1917 with water surface elevations at Kingston.

If the elevations at Tibbett's Point are "of but little value," and if the elevations at Kingston, Ontario are based on the Tibbett's Point

readings, then their accuracy must be doubtful. Furthermore, if the elevations at Port Dalhousie and Toronto are based on the Kingston float gage elevations, they must also be of questionable accuracy.

This chain of dependent elevations helps to explain why precise leveling (at its present state of accuracy) cannot be used to determine rates of crustal movement in the Great Lakes region (see pp. 87-90).

In view of the long history of the effect of topography and water depth upon the water-level and upon its recording at water-level gages, and especially in view of F. B. Taylor's explanation of the importance of gage site location with respect to the area of horizontality, it is difficult to understand why the importance of gage location to the calculation of rates of crustal movement was not realized by those investigators who determined rates of uplift for the Great Lakes region.

It is particularly difficult to understand how B. Gutenberg (1941, pp. 740-741) could say:

> From the fact that there is practically no relative change between Calumet Harbor and Milwaukee on Lake Michigan, and between Port Stanley and Cleveland on Lake Erie, it is concluded that the zero isobase runs to the north of these stations, and consequently that the zero assumed for these two lakes approximates the absolute zero. This agrees with the findings of Taylor (1926) that, at least since the time of the Nipissing Great Lakes, which was about 5000 years ago according to Antevs (1939), there has been no noticeable uplift in the region.

and then use Calumet Harbor, Milwaukee, Cleveland or Port Stanley as one gage of 10 pairs of gages out of a total of 14 gage pairs on Lakes Mighigan-Huron and Erie. It is obvious that uplift cannot be measured in an

area where uplift has stopped. Nor can accurate rates of uplift be found where one gage of a pair is in an area where uplift has stopped, the other gage is in an area of uplift, and the point between the two gages at which uplift begins is unknown.

GREAT LAKES RATES OF CRUSTAL MOVEMENT BY PRECISE LEVELING

One attempt has been made to determine absolute rates of crustal movement in the Great Lakes area by means of precise leveling. The results of this study are found in Sherman Moore's (1948) paper "Crustal Movement In The Great Lakes Area," pages 702-706 and Plate I.

As a result of the factors which are discussed in pages 87-90 of this paper and to several erroneous assumptions by Moore, these rates of crustal movement are not valid. The initial point for the determination of elevations for the Great Lakes area is Rensselaer (Greenbush), New York, and it is for this point that the first erroneous value for the rate of crustal movement was computed. If the initial rate of crustal movement is incorrect, the values for the other points in the leveling net are probably also incorrect.

Moore (1948, p. 702) stated:

> Between mean tide, or half tide, at New York, which at that point are practically identical, and Rensselaer, near Albany on the Hudson River, there are levels in 1857, 1877, and 1934, all run by the U. S. Coast and Geodetic Survey. By the levels of 1934, the land at Rensselaer is lower by 0.849 foot than by the levels of 1877, corresponding to a subsidence at a rate of 1.49 feet per 100 years. The elevation by the levels of 1857 falls only 0.02 foot from a line through the other two points. This early determination

has not been used, as it was considered less accurate than the later levels, but its inclusion would have had only a negligible effect on the rate.

The specious reasoning underlying the determination of this rate of subsidence at Rensselaer is revealed by an examination of the U. S. Coast and Geodetic Survey precise leveling elevations of benchmark Gristmill at Greenbush (Rensselaer), New York, and by the leveling net adjustments which were made by the Coast and Geodetic Survey.

The elevations (Comstock, 1876, p. 71; U. S. Deep Waterways Comm., 1897, pp. 70-71; Hayford, 1900, pp. 449, 540; Hayford, 1903, pp. 196, 289, 378, 555; Bowie, 1914, p. 105) are as follows:

| Year | Elevation in Feet |
|---|---|
| 1857[a] | 15.37 |
| 1877[a] | 14.728 |
| 1894[a] | 13.645 |
| 1899 | 13.577 |
| 1902 | 13.873 |
| 1903 | 13.863 |
| 1907 | 13.863 |
| 1912 | 13.865 |
| 1929 | 13.618 |
| 1934[a] | 13.845 |

[a]Level lines run by the U. S. Coast and Geodetic Survey.

The most recent determinations of bench mark Gristmill based on the 1929 adjustment (Gossett, 1961, letter) are as follows:

| | |
|---|---|
| 13.619 feet | (1902 leveling) |
| 13.553 feet | (1934 leveling) |
| 13.501 feet | (1955 leveling) |

The changes of elevation in the above paragraphs must be examined with the following facts in mind (see p. 84): (a) First order leveling

by the U. S. Coast and Geodetic Survey began in 1878; therefore the levels of 1857 and 1877 were not of first-order precision; (b) the first adjustment to the level net occurred in 1899, partial adjustments were made in 1903, 1907 and 1912, and a complete adjustment was made in 1929 (Rappleye, 1948a, p. 1). For these reasons the logical choice of the early elevation for Gristmill (bearing in mind the precision necessary to calculate rates of crustal movement) would be the elevation of 13.577 feet resulting from the first adjustment in 1899.

The explanation for the changes in elevations at Gristmill lies not only in the fact that better equipment and techniques were used in the later levelings (1894, 1934, 1955), but also to the fact that new leveling lines and better determinations of sea level were introduced into the precise leveling net with each adjustment or readjustment to the net. As was stated in the U. S. Deep Waterways Commission Report of 1897 (p. 71):

> In 1894 the Coast and Geodetic Survey ran a line of precise levels along the Hudson River, starting from the bench mark at Dobb's Ferry. The superintendent gives the elevation of the bench mark on the gristmill as 13.645 feet, with the following note: "The difference between the above (13.645) and any former results is probably due to the more perfect determination of tidal level than to any other cause.

In other words, the adjusted elevations are not necessarily the result of a subsidence or uplift at the bench mark, but, instead, represent the introduction of new information into the precise leveling net. The bench mark shifting shown by the elevations is almost purely a "paper" movement.

If the elevations for the years 1877 and 1894 had been used, the subsidence would have been 1.083 feet/17 years, or 6.37 feet/100 years; or, if the years 1899 and 1902 had been used, the subsidence would have been 0.296 foot/3 years or 9.87 feet/100 years.

In his section on "Reduction to Sea Level," S. Moore (pp. 704-705) states:

> For a correlated picture of the movement as a whole, the observations must be reduced to a common datum. The only practical datum for this purpose seems to be sea level. If one admits a changing sea level there is no means of determining whether the movement is uplift or subsidence. Great variations in the relative elevation of land and ocean level during geologic time seems well established, but it seems improbable that there has been any appreciable progressive change in the volume of oceanic water in the last 100 years.

As was discussed in pages 45-48, 56-58, of this paper, there is a world-wide change in sea level of c 0.36 foot/100 years, as well as a change in sea level at New York City (the starting point for Great Lakes leveling lines) corresponding to 0.78 foot/100 years. One can admit a changing sea level and by measuring the change and correcting for it, decide whether a movement is subsidence or uplift. The height of the ocean level in the geologic past has little or no bearing on the problem.

## Significance of Previous Determinations

An investigation of the gage histories of U. S. Lake Survey gages (Sherman Moore, 1939-1944) and of the gage histories of the Canadian Hydrographic Service emphasizes the many opportunities, particularly in

the earlier measurements, for error to enter into the determination of lake-level elevations due to equipment limitations, shifting bench marks, incorrect or lost records, observer mistakes, gage locations, etc.

Rates of crustal movement in the Great Lakes region are determined from the gage differences of pairs of gages. The gage differences include not only the changes due to land uplift, but also the residual effects of wind set-up, the barometric pressure effect, the changing differences in seiche amplitudes, tidal differences, observer error, instrument error, bench mark changes, etc. While it is very probable that many of these effects are small in magnitude, or that many of them are opposite in sign and thus compensate each other, nevertheless the errors caused by these effects must be recognized and removed, or corrected, so that the true magnitude of the uplift may be approached as closely as possible. Because the magnitude of land uplift is so small, the combination of the various errors which are preserved in the lake-level gage records tend to completely mask its effect and make its detection with present methods difficult, if not impossible.

The change in the character of a plot of gage differences over a period of 95-96 years is illustrated graphically by Fig. 5 which shows gage differences between gage pairs on Lake Ontario and Lake Erie. The great decrease in the fluctuations of the gage differences as operator and instrument error was reduced by means of improved equipment, gage locations and gaging techniques is readily seen.

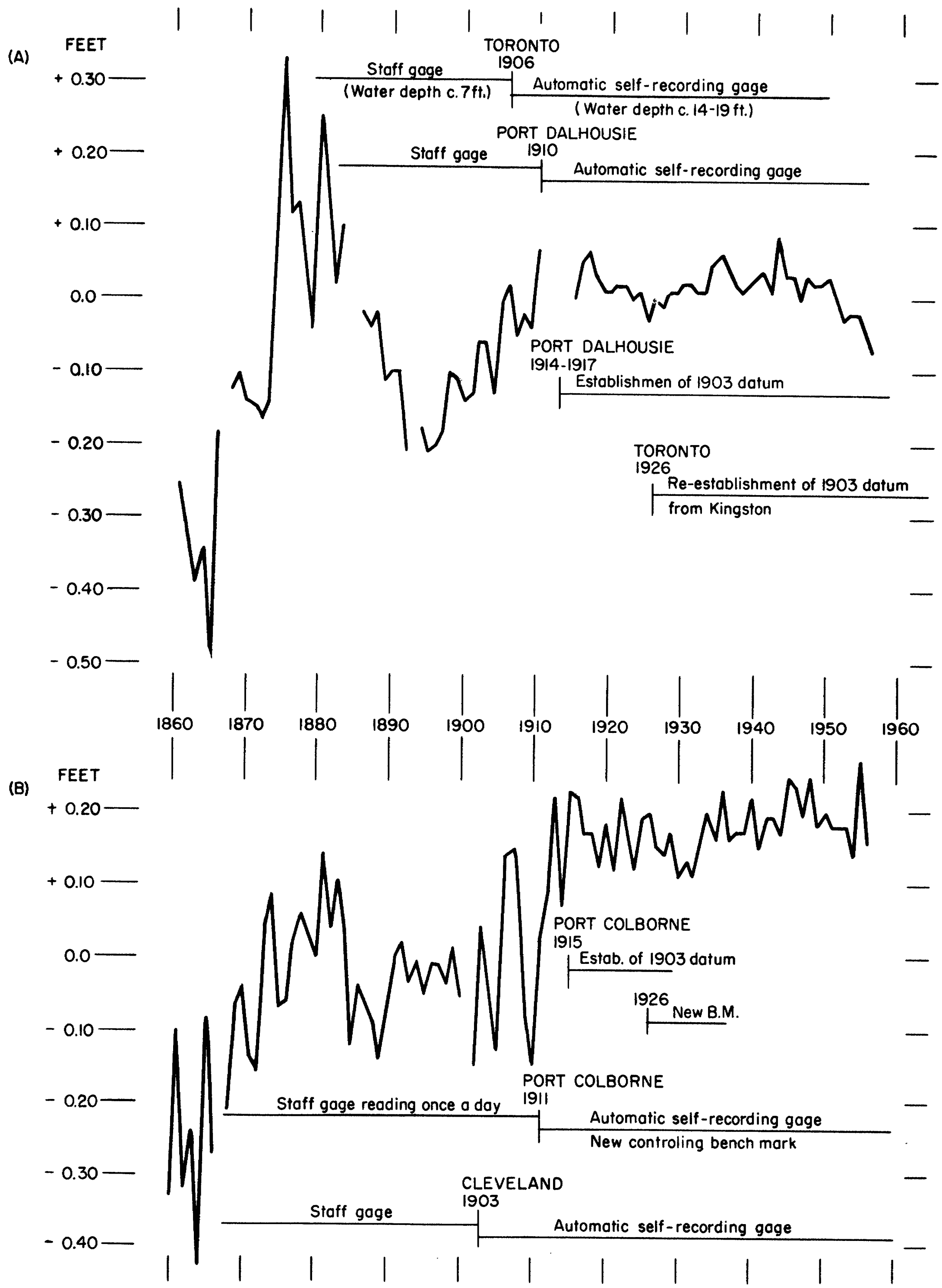



Fig. 5. Gage differences on Lake Ontario (A. Toronto minus Port Dalhousie) and Lake Erie (B. Cleveland minus Port Colborne) showing decrease in range of fluctuations with improved equipment, locations, and techniques.

The proportions of various types of error which distort true lake-level values changed throughout the period of record taking. In the earlier days of lake gaging, say before 1920, bench mark stability and instrument and operator error predominated, whereas the systematic errors caused by meteorological effects, tides, harbor effects, etc., were relatively small. After improved equipment, techniques, etc., removed the grosser aspects of instrument and operator error, the importance of meteorological effects, etc., grew proportionately.

At the present stage of lake-level gaging the greatest deviations from true lake-level elevations (on each lake—not referred to sea level) are due to meteorological effects and the effect of gage location. Before worth-while determinations of crustal movement can be made, corrections for these effects, as well as for the remaining instrument and operator errors, must be made.

The following section discussing modern rates of land uplift around Lake Erie points up the difficulties which arise when all of the aspects of a problem are not viewed in a coordinated manner—in this instance the failure to examine and analyze all aspects of the problem caused a case of "mistaken identity" to arise.

## LAKE ERIE

An examination of Plate I reveals that Lake Erie and its shores have been completely within the area of horizontality since Nipissing time, a period of approximately 3000 years. Despite the fact that no uplift has

occurred for 3000 years, all of the determinations of rates of crustal movement (with the exception of Horton and Grunsky, 1927, p. 32) have found uplift around Lake Erie—the rates varying from 0.009 foot/100 miles/100 years (Moore, 1948) between Cleveland and Port Stanley (Gutenberg, 1941, finds zero uplift for the same pair) to 1.04 feet/100 miles/100 years (Moore, 1922) between Cleveland and Amherstberg (see Table 3).

As postglacial uplift probably ceased about 3000 years ago, the rates of the quantity called "crustal movement" must in actuality be rates of some other quantity. Because Great Lakes water-level gage records are not corrected for the factors which were discussed in Part II of this paper (pp. 41-76), the previously determined "rates of crustal movement" measured the change in the net difference of the accumulated effects and errors (chiefly meteorological) which are incorporated in the gage records. The "rates of crustal movement" would be more accurately labeled "average net setup" for the period of record of a given pair of gages.

The same method is used to determine rates of crustal movement in the entire Great Lakes region, and as this method has yielded rates of crustal movement up to 1.04 feet/100 miles/100 years in an area where uplift had ceased several thousand years ago, and as this rate exceeds all of the Nipissing rates (Table 1) and all but two of the computed modern rates (Table 3), it is reasonable to assume that the value of the rates of modern crustal movement, even the existence of modern crustal movement, around the Great Lakes is in doubt.

## V. COMPUTATION AND CORRELATION OF METEOROLOGICAL EFFECTS AND GAGE DIFFERENCES

As has been pointed out previously, gage differences are the basis for computing rates of crustal movement and are also the basis for computing set-up between pairs of gages. The justification for using the same quantity as the basis for two entirely different phenomena is the assumption that winds over the Great Lakes in the summer months blow in opposing directions so that "the mean surface of each lake is level" (Comstock, 1882, p. 592) and, therefore, that set-up does not exist to any significant degree; consequently gage differences represent movement of the land between the gages of each pair.

If the winds over the Great Lakes do <u>not</u> neutralize each other's effects on the water surface during the summer months, i.e., if vector resultant winds from one quadrant predominate; then the wind from the prevailing direction will exert its influence and net set-up will occur in the direction of the prevailing wind. If net set-up does occur, a plot of the gage differences over a number of years will measure the average net set-up for that time, not the rates of crustal movement.

The crucial point is whether summer winds can produce a predominant summer vector resultant wind whose setup can be correlated with the magnitudes of the gage differences. If such a correlation can be shown, the rates of crustal movement which have been calculated heretofore are not valid.

Previous Statements of Westerly Prevailing Winds

Mark W. Harrington's (1895) comprehensive study <u>Surface Currents of the Great Lakes</u> included two tables of wind directions over the Great Lakes. In writing of the most frequent winds on the Great Lakes (as shown by compilation of tri-daily readings from 1871-1888) Harrington (p. vi) stated:

> If we take the months May to September, inclusive, the numbers are N., 1; NE., 12; E., 0; SE., 10; S., 16; SW., 29; W., 13; NW., 7. This is 88 for these months, of which 33 per cent are SW; 15 percent W; and 8 percent NW.; or 56 percent from a westerly direction.
>
> The prevailing character of the westerly winds at the lake station is shown still more clearly in the resultant wind directions (Table II):

The wind directions for the following stations were taken from Harrington's Table II (p. v):

| | June | July | Aug. | Sept. | Annual |
|---|---|---|---|---|---|
| Buffalo | S.44 W. | S.58 W. | S.49 W. | S.52 W. | S.57 W. |
| Duluth | N.13 E. | N.14 W. | N. 3 W. | N. 5 W. | N. 7 W. |
| Oswego | S.61 W. | S.72 W. | S.53 W. | S.20 W. | S.55 W. |
| Rochester | S.80 W. | S.88 W. | S.76 W. | S.67 W. | S.75 W. |
| Toledo | S.40 W. | S.64 W. | S.67 W. | S.35 W. | S.57 W. |

William T. Blunt's "Effects of Gales on Lake Erie" (1897, pp. 157-158, diagram no. 2) also contained tables and a graphic representation of winds as recorded at Toledo, Ohio (1891-95). Blunt's tables showed that winds from the southwest and west exceeded those from the northeast and east during eleven months of the year (including all of the summer months). Blunt (p. 158) stated that, "... the resultant movement and direction in the average months are most decidedly from the westward. ..." and "this

naturally tends to keep the mean level of the east end of the lake higher than that of the west end."

Wind directions of all stations, except Cleveland, around the American shore of Lake Erie (based on 15 years of observations), during the months of June, July, August and September blew from the southwest (from S 13° W to S 73° W) (Henry, 1902, p. 11). Regarding the wind directions at Cleveland, Ohio, A. J. Henry (p. 11) declared, "The unusually large number of southeasterly winds at this station is not clearly understood, unless as suggested by local forecast official Kenealy, of Cleveland, they are due to land and lake breezes."

A modern summary of Great Lakes wind velocities (USWB, 1959, pp. 13-14) confirms the earlier observations that the prevailing summer winds are from the southwest on Lakes Erie and Ontario and are from the westerly quadrant on Lakes Michigan, Huron and Superior.

As the preceding excerpts illustrate, it has been known for 60 or more years that the predominant wind direction for the Great Lakes is westerly; in addition, the prevailing southwesterly direction of summer winds on Lake Erie has also been recognized since the 1890's.

Because it has been known at least since the early nineteenth century (Dwight, 1822, p. 96; Hall, 1843, p. 200) that southwest winds on Lake Erie cause a rise of water level at the eastern end of the lake, and because it has also been known, since the 1890's (if not before), that southwest winds predominate during the summer months, it is surprising that the assumption that the summer season mean lake surface is

a level surface has been questioned only by William T. Blunt (see p. 102).

## Present Study

A review of the material in the preceding sections prompted the decision to test the validity of the assumption which underlies water-leveling, as well as the determination of rates of crustal movement; the test to be by correlating the gage differences of a pair of gages on the Great Lakes with summer wind velocities on the same lake.

For a number of reasons Lake Erie was an ideal location for the correlation study; the more important reasons being:

(a) Lake Erie is oriented so as to be almost parallel with the prevailing winds of the summer months.

(b) Water-level gages (at Toledo and Buffalo) are located at the ends of the lake, and the direction of a line from Toledo to Buffalo is within 3° of the direction of the lake's axis.

(c) First-order U. S. Weather Bureau stations record wind velocities relatively near (9-18 miles) the gage sites and at two other points where the lake is divided approximately into thirds (Cleveland and Erie).

(d) Lake Erie is shallow (average depth c 58 feet) and the gage sites are at the converging ends of the lake; both factors increase the magnitude of set-up, which in turn, amplifies the relationship which exists between wind velocities and set-up (gage differences).

(e) Lake Erie is located wholly within the Nipissing area of horizontality; therefore postglacial uplift could not have occurred during modern times, and the rates of crustal movement which have been calculated must represent some other quantity.

Similarly the gage differences of gage pairs in the other Great Lakes could also be correlated with wind velocities. The gage pairs chosen should meet three requirements:

(1) The direction between the gage sites of the pair of gages must parallel, at least roughly, the direction of postglacial uplift (i.e., one gage should be about N 70° E from the other).

(2) Both gages of a gage pair must be north of the Nipissing zero isobase, and

(3) There must be nearby weather stations which record wind velocities and whose records are available.

These requirements restrict testable additional gages to two pairs. One pair (Duluth-Port Arthur) is located on Lake Superior, and the other pair (Toronto-Kingston) is on Lake Ontario. Although these gage pairs fill the requirements better than any of the other available gage pairs, serious deficiences remain which greatly limit their usefulness; however the deficiencies serve to point out the need for more complete meteorological and lake-level data on the Great Lakes.

Owing to gage site locations as well as to the fact that the average angle between the summer wind direction (1950-59) and the direction of the

Duluth-Port Arthur axis was 41°, it is expected that the correlation between gage differences and wind velocities would be low. An examination of current charts of Lake Superior (Harrington, 1895, Lake Superior Chart; Millar, 1952, Fig. 5) reveals circumstances which would tend to support this expectation. The current from the area of Thunder Bay (Port Arthur) Ontario moves southwestward along the northwest shore of Lake Superior to an area somewhere between Grand Marais, Minnesota, and Devil's Island, Wisconsin, where it curves to the east. The current flowing along the northwest shore from Duluth moves northeastward to an area south-southwest of Grand Marais where it also curves to the east, or continues to curve around until it is flowing to the south-southwest. Thus the situation exists where the current direction at one gage is 180° from the current direction at the other gage; as setup is dependent upon the wind-drift current (which in this case is flowing in opposite directions) it is to be expected that a very low or non-existent correlation would be found.

The Toronto-Kingston gage pair on Lake Ontario meets the first two requirements satisfactorily, but proves to be inadequate on the third—that of nearby wind and barometric pressure observations. Wind and barometric pressures are recorded at the Class I weather station at Toronto at the western end of the lake, but records of wind velocities and barometric pressures are not available for the eastern end of Lake Ontario. The nearest available wind and barometric pressure observations were

taken at Trenton, Ontario, which is located only two-thirds of the distance from Toronto to Kingston. A gap in the Trenton records for the years 1953 and 1954 was filled in by wind observations taken at Main Duck Island. Main Duck Island has an excellent location in open water at the eastern end of the lake, but the observations were recorded by a radio beacon station which is a class c weather station (the Canadian Meteorological Division stations are classed as I, II, III and c). In addition the record at Trenton is available only to 1955.

Because wind and barometric pressure information is not representative of the eastern end of Lake Ontario (observations were made about 54 miles from Kingston), the correlation of gage differences between Toronto and Kingston and wind velocities should not be significant.

## Lake Erie Winds

### VECTOR WINDS

At the beginning of the study it was expected that mean wind velocities for the summer months could be obtained for the locations and years under investigation directly from the U. S. Weather Bureau _Local Climatological Data_ and the Canadian Meteorological Branch _Monthly Meteorological Summaries_. However it soon became apparent that prevailing wind directions and average speeds from these compilations were not suitable for calculating set-up or for correlating with gage differences.

The wind speeds and directions reported in the _Local Climatological_

Data are determined as follows:

> The prevailing wind directions for the month is the direction which has the greatest total number of hourly occurrences arrived at by the summation of hourly observations in Table B, Wind Direction and Speed Occurrences, published in the Local Climatological Data Supplement ... (Fox, 1960).
>
> Average Wind Speed... at the foot of the column, enter the sum of the daily average hourly speeds, and the average of these speeds as obtained by dividing the sum by the number of days in the month. ... (U. S. Weather Bureau, 1959).

Wind speeds and directions arrived at in this manner are suitable for work in climatology, for evaporation and cooling studies, etc., but not for work which is concerned with transport, in this study with the transport of water. The transport of water by a wind-drift current is dependent upon the wind stress, which in turn depends upon vector winds.

Because vector wind speeds and directions are not published (or, except in certain studies, determined) for the Great Lakes, it was necessary to compute the vector winds for Lakes Erie, Ontario and Superior. The length of time required to plot the wind vectors restricted the time period of correlation to ten years (1950-59) for Lake Erie and Lake Superior. The lack of wind information imposed the eight year period (1948-55) for Lake Ontario.

The procedure which was used to plot the vector winds is given in pages 138-141. Tables 7-66, (pp. 180-227 of Appendix II) contain the daily, monthly and summer season vector winds for: (a) Lake Erie—Toledo, Ohio, and Buffalo, New York, (b) Lake Ontario—Toronto, Ontario, and Trenton, Ontario, and (c) Lake Superior—Duluth, Minnesota, and Fort

William/Port Arthur, Ontario.

Over-water vector resultant winds computed for the summer season (June, July, August and September) for Lake Erie (1950-59) and Lake Ontario (1948-55) are summarized in Table 5. The summer season vector resultant winds for Lake Superior are land station winds because an over-water:land wind ratio has not been determined for Lake Superior.

All studies have indicated that the prevailing summer wind directions for Lake Erie and Lake Ontario are from the southwestern quadrant, and that the summer prevailing wind directions for the other Great Lakes are from the western quadrant. Winds blowing over the water surface from the southwest cause a net set-up to occur—the water surface being depressed on the windward shore and piled up on the lee shore (see Fig. 4b). The set-up is a tilt of the lake surface—the tilt being up toward the northeast.

Postglacial crustal movement in the Great Lakes region has consisted of an upwarping to the northeast; therefore when investigators (seeking to measure postglacial uplift by means of uncorrected lake-level gage readings compared with the presumed "level" summer lake surface) plotted gage differences for pairs of gages and found a northeast tilting, they apparently assumed that the change in gage differences was produced by crustal movement. Because investigators thought that the lake surface was level, whereas it was actually tilted upward to the northeast, the northeastern gages of the pairs appeared to be uplifted by the amount of the net set-up.

TABLE 5

A. LAKE ERIE OVER-WATER WINDS (JUNE-SEPTEMBER)
MEAN VECTOR RESULTANT WIND FOR TOLEDO-BUFFALO

| Summer Season Over-Water Vector Resultant Wind | | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | From | | mph | Year | From | | mph |
| 1950[a] | 214° | (SSW) | 265 | 1955 | 227° | (SW) | 304 |
| 1951 | 224° | (SW) | 518 | 1956 | 228° | (SW) | 582 |
| 1952 | 214° | (SW) | 576 | 1957[b] | 238° | (WSW) | 355 |
| 1953 | 223° | (SW) | 505 | 1958 | 240° | (WSW) | 735 |
| 1954 | 236° | (SW) | 592 | 1959 | 237° | (WSW | 445 |

[a]Based on three months (July, August, September)
[b]Based on three months (June, July, August)

B. LAKE ONTARIO OVER-WATER WINDS (JUNE-SEPTEMBER)
MEAN VECTOR RESULTANT WIND FOR TORONTO-TRENTON

| Summer Season Over-Water Vector Resultant Wind | | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | From | | mph | Year | From | | mph |
| 1948 | 280° | (W) | 464 | 1952 | 242° | (WSW) | 638 |
| 1949 | 253° | (WSW) | 460 | 1953[a] | 251° | (WSW) | 476 |
| 1950 | 260° | (W) | 598 | 1954[a] | 270° | (W) | 410 |
| 1951 | 252° | (WSW) | 480 | 1955 | 246° | (WSW) | 339 |

[a]Observations from Main Duck Island 1953-1954.

C. LAKE SUPERIOR LAND STATION WINDS (JUNE-SEPTEMBER)
MEAN VECTOR RESULTANT WIND FOR DULUTH-PORT ARTHUR

| Summer Season Land Station Vector Resultant Wind | | | | | | | |
|---|---|---|---|---|---|---|---|
| Year | From | | mph | Year | From | | mph |
| 1950 | 262° | (W) | 290 | 1955 | 266° | (W) | 109 |
| 1951 | 278° | (W) | 146 | 1956 | 337° | (NNW) | 86 |
| 1952 | 246° | (WSW) | 223 | 1957 | 278° | (W) | 115 |
| 1953 | 262° | (W) | 216 | 1958 | 266° | (W) | 320 |
| 1954 | 22° | (NNE) | 80 | 1959 | 218° | (SW) | 142 |

When gage differences were plotted for a number of years and a best-fit curve drawn, the slope of the curve was called the "rate of crustal movement;" in fact, the slope of the curve represented, for the most part, the average net set-up for the time period being considered.

It must be emphasized that the quantities which were determined and used in the following sections, i.e., gage differences, barometric pressures, and effective wind velocities, are net quantities; that is, they are residua of winds, barometric pressures, and wind and barometric pressure effects which occurred over the four month summer period. As quantities which do not represent phenomena that were actually observed, but rather averages of actual conditions, they should represent a quasi-steady state condition, and the relationships deduced from their study may or may not apply in detail to momentary, hourly or daily conditions.

## EFFECTIVE WINDS

Summer season over-water mean monthly vector winds (summer mean monthly winds) cannot be used directly in the computation of set-up, or in correlating gage differences with set-up—they must first be converted to effective winds, i.e., winds which represent that portion of the over-water wind which causes the observed setup at the gage sites.

Winds vary from 0% to 100% in effectiveness—100% effective winds are those winds which cause the observed gage differences (corrected for barometric pressure effects). Zero per cent effective winds are winds which blow at right angles to the 100% effective winds. Ideally, effective wind velocities when squared and plotted against corrected gage

differences would yield a + 1.0 correlation coefficient.

Effective winds are usually found by resolving vector resultant winds into their components; in this case, effective winds are functions of the cosines of the angles between the resultant wind directions and the direction of the lake axis (deviation angles). However, effective winds are defined as winds which cause the observed setup, and not as the simple components of resultant winds. Because resultant winds must exert their influence across the air-water interface, and because they blow over a curved surface and not a flat plane, effective winds may not be cosine functions of the resultant winds; instead they may bear some other relationship to resultant winds. With this possibility in mind, effective winds were computed in two ways: (1) one computation was made using the cosines of the deviation angles from 0-90 degrees; and (2) the other computation was made using a linear relationship, i.e., winds were considered to decrease 1.11% in effectiveness for each degree that the resultant wind directions deviated from the direction of a line connecting the two gages under investigation (see pp. 139-140).

The test to determine the correct method is by comparing the degree of correlation (shown by the correlation coefficient r) between the effective wind velocities squared and the observed gage differences corrected for barometric pressure effect. If winds from one particular direction are most effective in creating the set-up, the correlation coefficient for this direction and the set-up should be at a maximum. Thus the values of the correlation coefficients should increase as the wind directions

approach the 100% effective wind direction, be at a maximum at the 100% effective wind direction, and decrease as this direction is exceeded. If winds blow from a direction opposite to those which cause the quasi-steady state setup, i.e., they blow "down slope," they are called negative effective winds. For example, a wind that blows in a direction 180° from the direction of the 100% effective wind would be a -100% effective wind.

## Direction of Effective Wind

Previous investigators (Hellström, 1941, pp. 17-18; Keulegan, 1953, pp. 102-103; Harris, 1954, p. 38; Gillies, 1960, p. 37) have considered the 100% effective wind as blowing parallel to the lake axis, i.e., on Lake Erie the 100% effective wind would be from 248°. The choice of the lake axis direction as the 100% effective wind direction presumably follows the reasoning of V. W. Ekman's theory of currents which postulates that the rotation of the earth does not deflect surface currents in shallow water, and that, consequently, wind-drift currents flow in the direction of the wind. In addition, Ekman's theory proposes that the slope of the water surface will always be in the direction of the wind in water of <u>any</u> depth. Because these conclusions do not agree with the results of this investigation, Ekman's theory will be examined briefly in the light of the observations which prompted its formation.

V. Walfrid Ekman originated his now classic theory of ocean currents in 1902 at the suggestion of Fridtjof Nansen who discovered during the

drifting of the ice pack which held his ship, the "Fram," that the ice drift of a given wind deviated to the right of the wind direction. Following the original Norwegian publication of the theory in 1902, Ekman expanded his theory which was then published in 1905 as "On the Influence of the Earth's Rotation on Ocean Currents."

The theory represents conclusions deduced from a mathematical model of ocean currents incorporating several simplifying assumptions; these assumptions cause the model to differ from conditions as they exist in nature (see pp. 54-56). Ekman (1905) states several conclusions which are pertinent to this discussion as follows:

> Equations (5) then show that in the northern hemisphere the <u>drift current at the very surface will be directed 45° to the right of the velocity of the wind</u> (relative to the water).[1] In the southern hemisphere it is directed 45° to the <u>left</u>... (p. 8).
>
> The above-mentioned result, according to which the surface-current's deflection from the wind-direction, is invariably 45°, seems rather strange; one would indeed expect the earth's rotation to have less influence on the currents, the smaller its vertical component $\omega \sin \phi$ ... (p. 10).
>
> The angle $\alpha$ between the wind and the surface-current, is not exactly 45°, when the depth is finite. ... and the angle of deflection $\alpha$ consequently depends on the ratio between the depth of the sea $\underline{d}$ and the Depth of Wind-Current D. If $\underline{d}/D$ is a small fraction, $\alpha$ is small and the current goes nearly in the direction of the wind. As the depth increases, $\alpha$ is alternately smaller and greater than 45°. Thus for instance $\alpha = 21°,5$ for $\underline{d} = 0{,}25$ D, $\alpha = 45°$ for $\underline{d} = 0{,}5$ D, $\alpha = 45°,5$ for $\underline{d} = 0{,}75$ D, and $\alpha = 45°$ for $\underline{d}$ = D. When $\underline{d}$ is greater than D, the deviations from the mean value $\alpha = 45°$ are quite insignificant, and the motion takes place almost exactly as on the deep sea. (p. 13-14).
>
> ... The arrows represented without shaft-feathers give the direction of the slope; it is remarkable how nearly this direc-

> tion follows the wind's direction (common for the whole plate) whatever be the depth of water. This shows clearly that <u>the earth's rotation has no considerable deflecting influence on the mounting up of water, in a sea impelled over its whole area by the same wind</u> (although the currents themselves may deviate from the wind's direction). <u>Its influence on the absolute magnitude of the mounting up is also found to be rather moderate</u>, its effect being to diminish the inclination of the water-surface in the ratio 0,98 if $\underline{d}$ = 0,5D, in the ratio 0,77 if $\underline{d}$ = 1,25 D, 0,71 if $\underline{d}$ = 2,5 D, and exactly 2/3 if $\underline{d}$ is infinite (p. 37).

The above quotations represent the chief deductions relating to the angle between the wind direction and the surface wind-drift current, and between the wind direction and direction of water surface slope.

Although Nansen's original observations of the angle of deviation between wind direction and ice-drift are given as 20°-40° to the right of the wind (e.g., Ekman, 1905, p. 2; Sverdrup, <u>et</u> <u>al</u>., 1942, p. 492), an examination of Nansen's (1902; 1904) summaries of the original data reveals that the range of the deviation angles was not that uniform. Nansen's observations taken aboard the "Fram" from 1893-1896 are summarized in the histograms of Figs. 6 and 7 (the angles of deviation were compiled from Nansen, 1902, pp. 366-67, Table 9, Column 13).

The histogram of Fig. 6 shows the distribution of the frequencies of occurrence of the angles between the wind resultant and the direction of ice-drift (after correction for the permanent current). The majority of the angles are in the 20°-40° range, but wide variances exist, e.g., the maximum angle was 80° to the right of the wind, the minimum angle was 63° to the left of the wind, and mean angle was 28° (only 62% of Ekman's theoretical value).

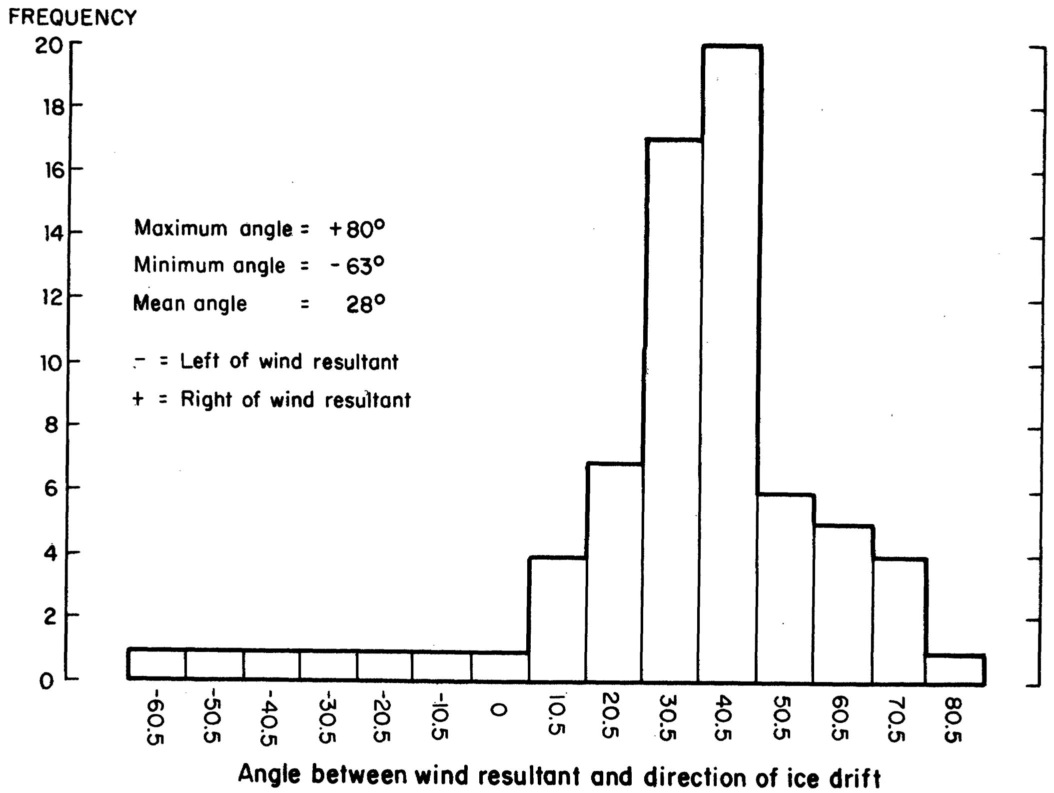



Fig. 6. Frequency of wind drift—wind resultant angles measured during drift of the "Fram," 1893-1896.

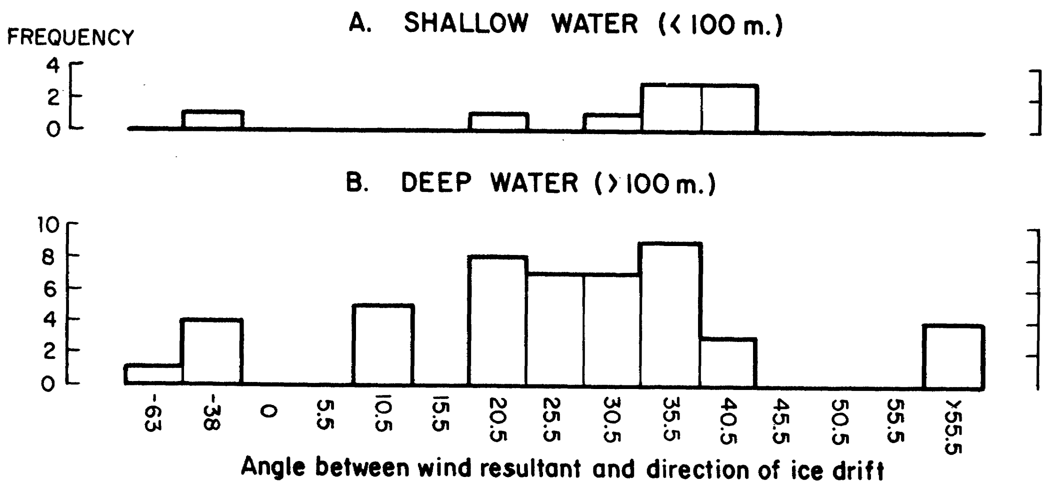



Fig. 7. Comparison of frequencies of drift deviation angles for soundings in: A. shallow (<100 m) and B. deep (>100 m) water.

Sounding information from Nansen's (1904, pp. 9-11) paper "The Bathymetrical Features of the North Polar Seas" was combined with wind-drift information from the 1902 paper to produce the histogram of Fig. 7—which represents the distribution of the angles of deviation of the ice-drift from the wind direction on the days when soundings were taken (56 soundings and deviation angles can be compared). The deep water histogram is the more interesting of the two histograms in that it shows that 40 of the 47 angles were less than 35° to the right, four angles were 59° to the right, and none of the angles fell in the 40.5°-55.5° range, whereas according to Ekman (1905, p. 10) the angle "is invariably 45°." The compilation also includes instances of deviation angles bearing to the left of the wind direction instead of to the right as required by the theory.

Nansen (1902, p. 378) gave the angle between wind drift and wind resultant as: (a) 26° from November 23, 1893, to November 23, 1894, (b) 34° from November 24, 1894, to November 28, 1895, and (c) 23° from November 28, 1895, to November 27, 1896. Other observations of the wind-drift direction angles confirm this lower range of values. For example, according to Sverdrup, _et al_. (1942, pp. 623, 666), Brennecke found the drift of the "Deutschland" in the Antarctic Weddell Sea to be 34° on the average, and Sverdrup reported the ice-drift over the North Siberian Shelf to average 33° to the right of the wind. In addition, G. E. Hutchinson (1957, p. 268) stated that R. Witting in 1909 measured

(109 observations) the angle of current deviation from the wind direction in water only 9 meters deep and found the deviation to be 33° to the right.

In each of these cases an explanation was advanced as to why the observed angles differed from the theoretical angle rather than why the theoretical value failed to conform to conditions as they were measured in nature. When empirical observations reveal a consistent difference between their values and the values obtained from a mathematical model of the phenomenon, it would appear that the model fails to account for some relationship which exists in nature, and for that reason it should be re-evaluated and adjusted so as to conform to natural conditions.

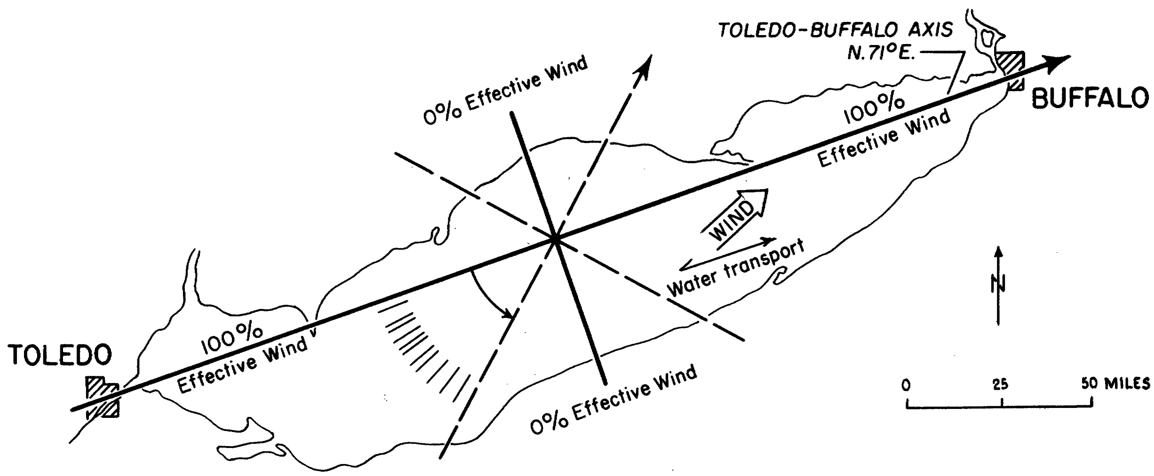
Ekman's statement that the slope of the water surface is always in the direction of the wind, rather than at some angle to the right of the wind, runs counter to intuitive reasoning of the subject. Because the surface slope is caused by the wind-drift current which flows at some angle to the right of the wind (in the northern hemisphere), it would seem that the surface slope should also be at a maximum in a direction at some angle to the right of the wind. In a study "The Effect of Steady Winds on Sea Level at Atlantic City," A. R. Miller (1957, p. 30) found that a nomogram relating the factors which cause departures from mean sea level indicated that a deviation angle of 20° gave the greatest slope if the assumption were made that the greatest departure takes place when net transport is normal to the coast-line. Miller (p. 30) stated that:

If the net transport represents surface drift and the gradient wind is replaced by geostrophic wind, the empirical angle of 20° is comparable to the computed angles ($\phi_o - \phi_s$ = 19° to 28°) between surface drift and gradient wind.

If Ekman's theory is followed, the direction of the effective wind would parallel the direction of a line connecting the two gages which record the water-surface levels; however, if, as suggested by Miller's nomogram, the slope occurs to the right of the wind, the effective wind would be from some direction to the right of a line connecting the gage sites.

Lake Erie, for reasons of geographical location, relatively uniform shallowness, wind measurements (first order weather stations around the lake) and water-surface measurements (levels taken by modern instruments and procedures), presents an excellent situation for testing Ekman's hypothesis of water-surface slope direction in shallow water.

As shown in Fig. 8, the direction of a line between the gage sites at Toledo and Buffalo is N 71° E. If Ekman were correct with regard to to slope direction, an effective wind blowing from S 71° W (251°) would give the best correlation with the observed gage differences corrected for barometric pressure effect. On the other hand, if the greatest slope occurs to the right of the wind direction, the wind showing the best correlation with the set-up (in this situation where the slope direction is fixed) should come from some direction to the right of the Toledo-Buffalo axis.




100% Effective wind considered as coming from:

| | | |
|---|---|---|
| 251° (On axis) | 235° (16° Right) | 218° (33° Right) |
| 248° ( 3° Right) | 233° (18° Right) | 213° (38° Right) |
| 243° ( 8° Right) | 230° (21° Right) | 208° (43° Right) |
| 240° (11° Right) | 228° (23° Right) | |
| 238° (13° Right) | 223° (28° Right) | |

Fig. 8. Lake Erie effective wind directions. Relationship of wind directions to 100% effectiveness in creating observed setup at Toledo and Buffalo.

## VECTOR WIND AND EFFECTIVE WIND PLOTTING PROCEDURE

The procedure outlined below was used to convert land station wind directions (prevailing) and speeds (average) to vector quantities. Wind directions and speeds for American stations were taken from the U. S. Weather Bureau's <u>Local Climatological Data Supplements</u> and those for Canadian stations were obtained from Meteorological Division's <u>Monthly Meteorological Summary</u>.

The plotting procedure for vector winds is as follows:

(a) The four synoptic hour observed winds (or winds recorded closest to the hours of 0100; 0700; 1300; 1900) were plotted as vectors (scale of 1 in. = 5 mph); their resultant, when divided by four, gave the daily mean vector wind at the land station concerned.

(b) In order to obtain over-water vector winds for the lakes under investigation, the daily land station mean vector winds were converted to over-water vector winds by applying empirically derived over-water; land ratios. These ratios which have been determined only for Lake Erie (Hunt, 1958, pp. 28, 30) and Lake Ontario (Bruce and Rodgers, 1959, pp. 10-11) are as follows:

(i) Toledo:—$V_{water}/V_{land}$ = 1.59 for June-September, 1950-59, with the exception of June, 1950, 1952-54, and July, 1955, when $V_w/V_l$ = 1.13;

(ii) Buffalo:—$V_w/V_l$ = 1.13 for June-September, 1950-59, with the exception of June, 1950, when $V_w/V_l$ = 0.90, and September, 1956, when $V_w/V_l$ = 1.59:

(iii) Lake Ontario:—(Bruce and Rodgers "spring") $V_w/V_l$ = 1.60 for June and July.

(iv) Lake Ontario:—(Bruce and Rodgers "fall") $V_w/V_l$ = 1.90 for August and September.

(c) The 30 (or 31) daily over-water mean vector winds were plotted on a scale of 1 in. = 10 mph to secure the monthly over-water vector resultant winds. Monthly mean daily vector winds were found by dividing the value of the monthly over-water vector resultant winds by the number of days in the month.

(d) The number of monthly over-water resultant winds corresponding to the number of stations used were plotted (scale 1 in.=50 mph) as a progressive vector plot in which the June wind velocity of one station was drawn to scale, being followed by the June wind velocity at the other station; the wind velocities for July, August, and September were plotted similarly. The vector sum was divided by the number of stations (two) to get the summer season over-water vector resultant wind [to be called the summer resultant wind] for the lake under discussion.

(e) The summer resultant wind divided by four gave the summer season over-water mean monthly vector wind [hereafter called the summer mean monthly wind].

(f) Summer mean monthly winds were converted to effective winds before the relationships with set-up were determined.

Effective winds on Lake Erie were determined by two methods: (a) the first method is based on the assumption that the effective wind is a linear function of the vector wind; (b) the second method considers the effective wind to be a cosine function of the vector wind. Using the first method, the effectiveness of a given wind was found by: (a) subtracting the wind direction from the 100% effective wind direction to get the deviation angle, (b) multiplying the deviation angle by 1.11% ($90° = 100\%$) to obtain the percentage of ineffectiveness, (c) subtracting the percentage of ineffectiveness from 100% to get the effectiveness percentage, and (d) multiplying the resultant wind speed by the effectiveness percentage to get the effective wind speed. For example, if the

direction of the 100% effective wind were 250°, winds from 160° and 340° would have zero effectiveness; winds from 70° would be -100% effective; and winds from, say, 220° and 280° would be 66.7% effective. Following the second method, the effectiveness of a wind was computed by: (a) determining the cosine of the deviation angle (equal to 100% effective wind direction minus the given wind direction), (b) multiplying the cosine by 100 to get the percentage of effectiveness, and (c) multiplying the vector wind speed by the effectiveness percentage to get the effective wind speed.

The resulting summer season over-water mean monthly effective vector winds [called effective wind or "V"] were then squared because wind stress, and thus setup, is a function of the wind velocity squared (see pp. 51-53). The quantity $V^2$ was used in wind-slope calculations, correlations, etc.

The effective wind velocities for Lake Erie which were computed from the summer mean monthly winds (1950-59) for 13 directions from 251° (on axis) to 208° (43° to the right of axis) are given in Table 67 (Appendix II, p. 228). These effective wind velocities were squared and correlated with summer season mean corrected gage differences for the same years.

## Correlation of Effective Winds and Wind Slopes

Observed gage differences are composed of wind slopes and barometric pressure effects; therefore, the effect of barometric pressure differences

must be computed and subtracted from the gage differences before the gage differences can be correlated with the effective winds. Barometric pressure effects were computed following the method on p. 229 (Appendix II) for Lake Erie (1950-59) and Lake Ontario (1948-55); the results of which are given in Tables 68 and 69 (Appendix II, pp. 231-232).

The wind slopes (set-up) which remained after the barometric pressure effects were removed from the gage differences were then correlated and regression lines determined for each of the 13 directions listed in Fig. 8. The regression lines and correlation coefficients were calculated by standard formulas (Wallis and Roberts, 1956, pp. 534-535; Goedicke, 1953, p. 163). The regression line formula

$$y = a + bx \quad \underline{\text{or}} \quad y = bx + a \tag{10}$$

was used,

where:

$a$ = intercept

$b$ = slope

$x = V^2$ = effective velocity squared

$y$ = gage difference

and where

$$b = \frac{\epsilon xy - \frac{(\epsilon x)(\epsilon y)}{n}}{\epsilon x^2 - \frac{(\epsilon x)^2}{n}} \tag{11}$$

$$a = \frac{\epsilon y}{n} - b\,\frac{\epsilon x}{n} \tag{12}$$

Correlation coefficients were computed by means of the formula

$$r = m\frac{\sigma_x}{\sigma_y} = \frac{\overline{xy} - \bar{x}\,\bar{y}}{(\sqrt{\overline{x^2} - \bar{x}^2})(\sqrt{\overline{y^2} - \bar{y}^2})}$$

where:

$$m = \text{slope} \quad \left[ m = \frac{\overline{xy} - \bar{x}\,\bar{y}}{\sigma_x^{\,2}} \right]$$

The results of the computation of correlation coefficients and regression lines using a linear relationship for effective winds and vector winds (13 directions) are given in Table 70 (Appendix II, p. 233). Six selected correlation coefficients and their effective wind speeds computed by the cosine method are given in Table 71 (Appendix II, p. 234). A summary of the effective wind directions considered as the 100 per cent effective wind, together with their correlation coefficients, is given below. After a direction was selected as the 100 per cent effective direction, summer mean monthly vector winds for 1950-1959 were converted to effective winds using the selected direction as the direction of the 100 per cent effective wind; these effective wind velocities were squared and correlated with observed set-up. This procedure was followed for 13 directions (from a direction parallel to the Toledo-Buffalo axis to a direction 43° to the right of the Toledo-Buffalo axis); the purpose was to determine the 100 per cent effective wind direction which would correlate most closely with the observed set-ups (corrected for barometric pressure effect).

The fact that a correlation coefficient of 0.76 for ten pairs of observations has less than a 1 per cent chance of arising accidentally (Herdan, 1960, p. 166) points out the significance of the following correlation figures where 11 of the 13 coefficients were considerably greater than 0.76.

| 100% eff. wind from | wind from degrees to rt. of axis | correl. coeff. (cos.) | correl. coeff. (linear) |
|---|---|---|---|
| 251° | 0° | 0.90 | 0.84 |
| 248° | 3° | 0.91 | 0.84 |
| 243° | 8° | | 0.85 |
| 240° | 11° | | 0.85 |
| 238° | 13° | | 0.87 |
| 235° | 16° | | 0.90 |
| 233° | 18° | | 0.92 |
| 230° | 21° | 0.94 | 0.95 |
| 228° | 23° | 0.93 | 0.98 |
| 223° | 28° | 0.93 | 0.94 |
| 218° | 33° | | 0.84 |
| 213° | 38° | | 0.72 |
| 208° | 43° | 0.89 | 0.68 |

The correlation coefficients computed from plots of effective winds considered as cosine functions of the vector winds and gage differences ranges from 0.89 to 0.94; there is little change in the value of the coefficients whether the wind is blowing along the direction of the Toledo-Buffalo axis or from a direction 43° to the right of the axis. In this case, it would appear that there is no definite 100 per cent effectiveness direction within at least 43° of the Toledo-Buffalo axis. On the other hand, the correlation coefficients resulting from effective winds assumed to have a linear relationship with vector winds shows the corre-

lation coefficients increasing to a maximum (the 100 per cent effective direction), then decreasing in value as the 100 per cent effective direction is passed.

The progressive increase in the correlation coefficient (r) from 0.84 when the wind is blowing along the Toledo-Buffalo axis direction to 0.98 when the wind is from 23° to the right of the axis, followed by a decrease in the value of r as the deviation angle exceeds 23°, suggests very strongly that the wind slope in Lake Erie occurs about 23° to the right of the wind, and, therefore, that the wind-drift surface current also flows about 23° to the right of the wind.

The very high correlation coefficients (up to 0.98) were unexpected in light of the errors discussed in pp. 68-76, as well as to the fact that wind velocities were determined at only two weather stations (Toledo and Buffalo). The only obvious solution seems to be that compensating errors have occurred and that vector wind velocities at Toledo and Buffalo (when converted with Hunt's ratios) are representative samples of the winds which blow over Lake Erie.

The very close correlation between effective wind velocities and corrected gage differences leaves little doubt that the observed gage differences are actually wind slopes (net set-up), and consequently are not measures of crustal movement. The correlation also brings out the fact that the greater part of the error in modern lake-level records for Lake Erie, and probably for the other Great Lakes as well, is due to meteorological effects.

Lake Erie "Hindcast"

A "hindcast" of calculated gage differences for 1950-59 was prepared in an effort to test the validity of the assumption that the observed gage differences are due to wind slope and barometric pressure effect. The wind slope was calculated from the regression line for winds from 23° to the right of the Toledo-Buffalo axis (wind slope = $1.250 \times 10^{-5} V^2 - 0.2543$) and barometric pressure effects were taken from Table 68 (Appendix II, p. 231). The results of these calculations are given in Table 6 (Appendix II, p. 179) and are compared graphically with observed gage differences in Fig. 9. [Note: The calculations were carried to three or four decimal places before the final rounding-off to two places in order to reduce the rounding-off error.]

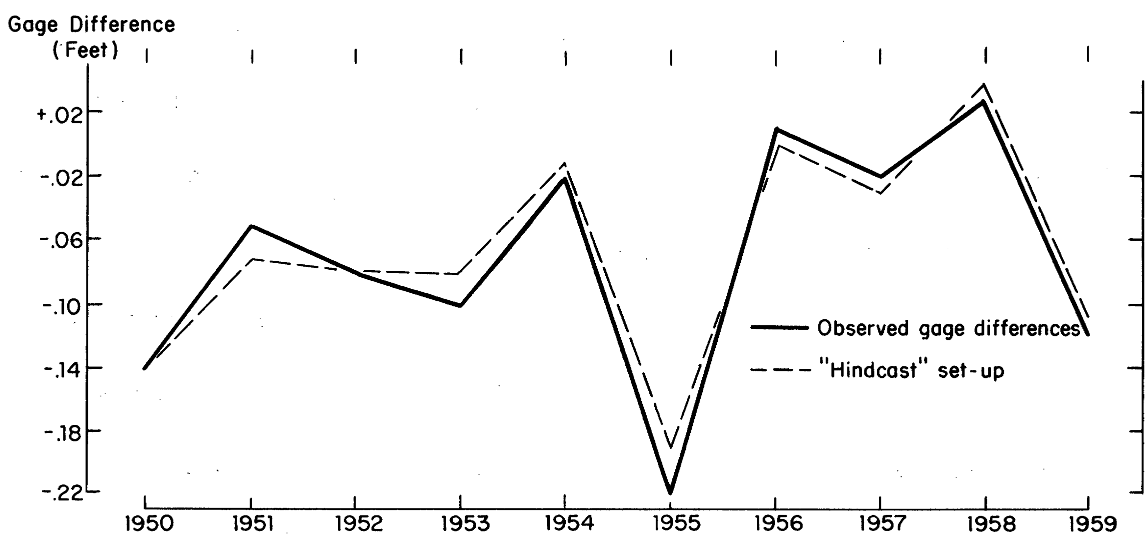



Fig. 9. Lake Erie "hindcast" set-up compared with observed gage differences for the summer seasons of 1950-59. Hindcast set-up = calculated wind slope + barometric pressure effect.

The comparison of observed gage differences and predicted set-up in Fig. 9 aids in emphasizing the fact that the observed gage differences are due almost wholly to meteorological effects, that the summer season mean lake surface is not level, and that uncorrected gage differences cannot be used in the calculation of rates of crustal movement.

## Present Status of Great Lakes Rates of Uplift

The correlation studies of wind velocities and gage differences together with information derived from the isobases of former shoreline features permits a résumé to be made of the validity of rates of crustal movement in the Great Lakes region which have been calculated up to the present time.

Postglacial uplift around Lake Erie ceased several thousands of years ago, and the quantities called "rates of crustal movement" are chiefly meteorological effects. Therefore all post-Nipissing rates of uplift for this lake are erroneous.

All of the gage pairs on Lakes Michigan and Huron are either in the area of horizontality, or have one gage of the pair in the area of horizontality. For this reason all previously determined rates of uplift for these lakes are not valid. Future determinations of possible uplift on Lake Michigan and Lake Huron must be determined from gage pairs which meet the requirements listed on page 122, and corrected gage records must be used for the determinations of uplift.

Gage differences, therefore calculated rates of uplift, from gage pairs north of the area of horizontality on Lake Ontario are probably, for the most part, the result of meteorological effects; however, lack of data prevents a proper correlation study of wind velocity and gage differences from being made. When the necessary wind information and lake-level information becomes available, it will be possible to determine whether gage differences represent net set-up, uplift, or a combination of the two factors.

Most of Lake Superior lies to the north of the Nipissing zero isobase; therefore it is possible that postglacial uplift is occurring around Lake Superior. Although uplift may be taking place around Lake Superior, the present gage sites are so located that it is impossible to determine whether gage differences are caused by uplift, wind slope, or some other factor. In the future, if the necessary meteorological stations and lake-level gages are established, it should be possible to separate gage differences into their component parts and to determine if one component represents postglacial crustal movement.

Before accurate rates of postglacial uplift can be measured in those areas where it may exist, it will be necessary to revise present procedures for obtaining lake-level gage differences so as to eliminate, or compensate for, the influences and errors which have been discussed in the preceding pages. If the essential meteorological and lake-level data become available, and if the necessary precautions are taken and

corrections made, then it will be possible to determine whether or not postglacial crustal movement exists in the Great Lakes region. In addition, if uplift is now taking place in this region, accurate measurements of its rate may be made.

# VI. CONCLUSIONS

1. Up to the present the only accurate rates of postglacial crustal movement in the Great Lakes region are those based on the elevations of former shoreline features of late glacial and postglacial lakes. Such rates are derived from the differences in elevation between the zero isobases and the isobases of maximum deformation—differences which are measured in tens or hundreds of feet and which result from thousands of years of differential warping.

The magnitude of these quantities is great enough for elevations determined by ordinary methods of spirit leveling to give accurate rates of crustal movement.

Rates of uplift calculated from isobases of former shorelines are to be contrasted with modern rates of uplift for the Great Lakes region determined from water-level gage records taken over periods of tens of years. In addition, the differences in elevation of the gages are measured in hundredths of a foot, tenths of a foot and, in some cases, in feet.

2. Modern land uplift due to postglacial isostatic rebound can occur only to the northeast of the Nipissing zero isobase, i.e., northeast of the Nipissing area of horizontality. Because postglacial crustal movement cannot occur in the Nipissing area of horizontality all rates of uplift on Lake Erie are invalid; furthermore, in the other Great Lakes all rates of uplift which are based on pairs of gages in which one gage

of the pair is south of the Nipissing zero isobase are also invalid.

3. Owing to a number of reasons (including the failure to consider the rise of mean sea level at the tide gage in New York City; mistaking the changes of elevation of bench mark Gristmill at Rensselaer, New York, which were caused by better determinations of sea level and adjustments of the precise leveling net for actual uplift; the inclusion of errors which have been discussed in this paper, etc.) the only determination of absolute rates of uplift by precise leveling in the Great Lakes region is valueless.

4. The choice of the tide gage at Father Point, Quebec, as the initial point for the precise leveling establishing the new International Great Lakes Datum was a dubious one. The Father Point tide gage is only about 400 miles from the former Laurentide ice divide; thus it is within the area of uplift. The gage is at the narrow end of the converging shores of the Gulf of St. Lawrence and the estuary of the St. Lawrence River. This situation increases the influence of meteorological effects. These factors (if corrections are not made) would prevent precise levelings made a number of years apart from being compared to the same datum.

5. Water-level gage records furnishing the basic data for water-leveling and modern rates of crustal movement contain errors which reduce the accuracy of elevations in the Great Lakes region, and which render valueless previously determined rates of crustal movement. The errors include those caused by meteorological effects, gage location effects, instrument error, and operator error. Early gage records of the Great

Lakes (up to about 1920) contained a greater proportion of instrument and operator error than error due to meteorological effects; gage records since that time, however, have an increased proportion of error due to meteorological effect owing to the reduction of operator and instrument error.

6. The influence of the disturbing factors must be removed or rendered insignificant if gage readings are to be an accurate representation of the actual elevation of the lake surface, or if the records are to be used in the determination of uplift.

Reduction in the size of errors due to meteorological effects, as well as to the effects of gage location, can be brought about by removing the water-level gages from their present locations near population centers and shallow water, and relocating them at sites in deep water away from harbors, bays, rivers, inlets, and areas of man-made changes in the configuration of the shoreline and underwater topography.

7. The assumption that the summer mean lake surface is level (the assumption which underlies the practice of water-leveling and the calculation of modern rates of postglacial crustal movement) is shown to be incorrect by the calculation of vector winds from Lake Erie and Lake Ontario for the summer months (June, July, August and September) of the years 1950-59 (Lake Erie) and 1948-55 (Lake Ontario). These determinations reveal a net vector wind from the southwest quadrant—a net vector wind which causes a net set-up between water level gages located at opposite ends of the lakes. The set-up is expressed as a tilt in the lake surface

upward to the northeast.

8. Rates of crustal movement calculated from best-fit curves of gage differences versus time represent, in the large part, the average net set-up between the gages of each pair for the time period plotted. This is demonstrated by the correlation of effective wind velocities on Lake Erie for the summer months of 1950-59 with gage differences of water-level gages at Toledo, Ohio, and Buffalo, New York. The correlation coefficient, r, was 0.98 with a 100 per cent effective wind direction from 23° to the right of the Toledo-Buffalo axis.

9. Definitive correlation studies of wind velocities and gage differences necessary for the determination of the existence, or of the rates, of uplift cannot be made for Lakes Ontario, Huron, and Superior until extensive wind, barometric pressure, and lake-level data become available for the eastern end of Lake Ontario and the northern and northeastern shores of Lake Huron and Lake Superior. When the necessary data are available, it will be possible to determine whether gage differences represent net setup, uplift, or a combination of these factors.

10. Ekman's classic theory of ocean currents, which represents conclusions deduced from a mathematical model of ocean currents incorporating many simplifying assumptions, should be re-examined and modified on the basis of empirical observations. This recommendation is supported by an analysis of Nansen's original observations (the basis for Ekman's theory) which revealed wide discrepancies between the observations and the results of Ekman's theory.

11. The correlation study of water-level gage differences and effective winds on Lake Erie presents an excellent opportunity to test Ekman's assumption that the direction of the water-surface slope is always in the direction of the wind, and provides a new technique for determining the angle between the direction of water-surface slope and wind direction.

12. The Lake Erie correlation study (effective winds [computed as linear functions of vector winds] vs. gage differences corrected for barometric pressure effect) indicated that the observed water-surface slope was caused by effective winds whose 100 per cent effective wind was from 23° to the right of the Toledo-Buffalo axis.

13. As the wind slope is caused by the wind-drift current, and as the wind slope is caused by wind blowing from about 23° to the right of the slope direction; then the wind-drift current is also caused by a wind blowing from about 23° to the right; or, expressed another way, the surface wind-drift current on Lake Erie will be directed about 23° to the right of the wind.

14. The thermocline established during the summer months probably acts as a temporary bottom. Therefore, if the thermocline acts as a quasi-bottom, and since the depth to the thermocline is approximately the same in all of the Great Lakes; then the angle of deviation of surface currents from wind direction for Lake Erie (23° to the right of the wind), should also be representative of the angle of deviation for the other Great Lakes.

## VII. BIBLIOGRAPHY


Airy, G. B., 1855, On the computation of the effect of the atraction of mountain-masses, as disturbing the apparent astronomical latitude of stations in geodetic surveys: Royal Soc. [London] Philos. Trans., v. 145, pt. 1, p. 101-104.

Akers, James, compiler, 1938, Drift thickness map: Michigan Dept. Conserv., Geol. Survey Div., no. 3528.

Am. Geol. Inst., 1957, Glossary of geology and related sciences: Washington, D.C., Am. Geol. Inst., 325 p.

Anderson, Einar, 1955, Adjustment of observations by the methods of least squares: Geod. Inst. Schr. [Copenhagen], ser. 3, v. 22, p. 7-8.

Avers, H. G., 1931, The determinations of elevations, in Figure of the earth, physics of the earth - II, no. 78: Washington, D.C., Natl. Research Council, p. 215-216.

✓Ayers, J. C., 1959, Great Lakes waters, their circulation and physical and chemical characteristics: Am. Assoc. Adv. Sci. Symposium on the Great Lakes Basin, Chicago, paper, Dec. 29-30, 1959, 15 p. (mimeographed).

✓________ and others, 1956, Currents and water masses of Lake Huron: Great Lakes Research Inst. Pub. No. 1, [now Great Lakes Research Div., Inst. Sci. and Tech] Mich. Univ., 101 p.

✓________ and others, 1958, Currents and water masses of Lake Michigan: Great Lakes Research Inst. Pub. No. 3, [now Great Lakes Research Div., Inst. Sci. and Tech.] Mich. Univ., 169 p.

Barrell, Joseph, 1915, Factors in movements of the strand line and their results in the Pleistocene and Post-Pleistocene: Am. Jour. Sci., ser. 4, v. 40, no. 235, p. 1-22.

Baum, W. A. and Havens, J. M., 1956, Recent climatic fluctuations in maritime provinces: Trans. 21st. North Am. Wildlife Conf., v. 21, p. 436-453.

Beals, C. S., 1953, Report of the special committee on the geophysical and geological study of continents, 1951-1952: Trans. Am. Geophys. Union, v. 34, no. 2, p. 281-292.

Beers, Yardley, 1953, Introduction to the theory of errors: Cambridge, Mass., Addison-Wesley Publ. Co., 65 p.

Bell, Robert, 1879, Report on an exploration of the east coast of Hudson's Bay 1877: Canada Geol. Survey Rept. of Prog. for 1877-78, pt. c, sec. V, 37 p; pt. cc, sec. VI, 31 p.

________1880, Report on explorations on the Churchill and Nelson Rivers and around God's and Island Lakes 1879: Canada Geol. Survey Rept. of Prog. for 1878-79, pt. c, sec. IV, 68 p.

________1897, Rising of the land around Hudson Bay: Smithsonian Inst. Ann. Report, p. 359-367.

Bentley, C. R. and Ostenso, N. A., 1961, Glacial and subglacial topography of west Antarctica: Jour. Glaciology, v. 3, no. 29, p. 882-910.

Bergsten, Folke, 1930, Changes of level on the coast of Sweden; Geog. Ann. [Stockholm], v. 12, no. 1, p. 21-55.

Bird, J. B., 1954, Postglacial marine submergence in central Arctic Canada: Geol. Soc. America Bull., v. 65, no. 5, p. 457-464.

Bjerknes, Jakob, 1959, The recent warming of the North Atlantic, in The atmosphere and the sea in motion: New York, The Rockefeller Inst. Press, p. 65-73.

Blunt, W. T., 1897, Effects of gales on Lake Erie, in U.S. Deep Waterways Comm. Rept. [U.S. House of Representatives. Doc. No. 192, 54th Congress, 2d session]: Washington, D.C., U.S. Govt. Printing Office, p. 155-168.

Bomford, Guy, 1952, Geodesy: Oxford, Clarendon Press, 452 p.

Bowie, William, 1914, Fourth general adjustment of the precise level net in the United States and the resulting standard elevations: U.S. Coast and Geodetic Survey Spec. Pub. No. 18, 328 p.

________1929, Tilting of mean sea level: Gerlands Beitr. zur Geophysik [Leipzig], v. 23, p. 97-98.

________1931, Isostasy, in Figure of the earth, physics of the earth-II, no. 78: Washington, D.C., Natl. Research Council, p. 103-105.

Bouguer, Pierre, 1749, La figure de la terre: Paris, Chez Charles-Antoine Jombert, 394 p.

Braaten, N. F., 1959, Orthometric, dynamic, and barometric heights, in Contemporary geodesy: Am. Geophys. Union Geophys. Mon. No. 4, p. 37-38.

Brooks, C. E. and Carruthers, N., 1953, Handbook of statistical methods in meteorology; London, Her Majesty's Stationery Office, M. O. 538, 412 p.

Bruce, J. P. and Rodgers, G. K., 1959, The water balance of the Great Lakes system: Am. Assoc. Adv. Sci. Symposium on the Great Lakes Basin, Chicago, paper, Dec. 29-30, 1959, 22p. (mimeographed).

Brunt, David, 1931, The combination of observations, 2nd. ed: Cambridge, Cambridge Univ. Press, 239 p.

Buch, L. F. von, 1813, Travels through Norway and Lapland during the years 1806, 1807, and 1808 [translation by John Black]: London, Henry Colburn, 460 p.

Burger, J. M., and Collette, B. J., 1958, On the problem of the post-glacial uplift of Fennoscandia: Koninkl. Nederlandse Akad. Wetensch, Proc., ser. B, v. 61, no. 4, p. 229-232, 235-241.

Burhark, R. K., 1959, Geodesy for the layman: St. Louis, Missouri, Aero. Chart and Info. Center, U.S. Air Force, 77 p.

Campbell, N. R., 1957, Foundations of science: New York, Dover Pubs. Inc., 565 p. [pt.II].

Canadian Hydrographic Service, no date, Monthly mean water surface elevations for Lakes Erie, Ontario, and Superior [1948-1959]: Ottawa, Ontario, (transcopy).

________no date, Precise leveling and gage histories for Lakes Ontario, Erie, Huron, and Superior: Ottawa, Ontario, 65 p. (transcopy).

Canada Meteorological Div., no date, Monthly meteorological summaries [1948-1959]: Toronto, Ontario, Canada Meteorol. Div., Dept. of Transport (mimeographed).

________no date, Summer wind records, Main Duck Island (1954-55): Toronto, Ontario. (photostats).

Canada Natl. Research Council, 1955, I. Geodesy: Canadian Geophys. Bull. [Ottawa], v. 8, Dec. 1955, p. 2.

Charlesworth, J. K., 1957, The Quaternary Era with special reference to its glaciation, Vol. II: London, Edward Arnold (Pub.) Ltd., 1700 p.

Chrystal, G., 1908a, An investigation of the seiches of Loch Earn by the Scottish Lake Survey, Part I Limnographic instruments and methods of observation: Royal Soc. Edinburg Trans., vol. 45, p. 361-387.

________1908b, An investigation of the seiches of Loch Earn by the Scottish Lake Survey. Part IV. Effect of meteorological conditions upon the denivellation of lakes: Royal Soc. Edinburgh Trans., vol. 46, pt. 3, no. 20, p. 455-517 [1909].

Clark, David, 1957, Plane and geodetic surveying, 5th. ed: vol. 2, higher surveying: London, Constable and Co., 673 p.

Clark, James, 1855, On the effect of the pressure of the atmosphere on the mean level of the ocean: Am. Jour. Sci., ser. 2, vol. 19, p. 52-55.

Clinton, De Witt, 1814, A discourse delivered before the New York Historical Society at their anniversary meeting, 6th December, 1811: New York Hist. Soc. Coll., v. 2, p. 37-116 [p. 94-95].

________1827, On certain phenomena of the Great Lakes of America: Edinburgh Jour. Sci., v. 7, pp. 290-298.

Cochran, W. G. and Cox, G. M., 1957, Experimental designs, 2nd ed.: New York, John Wiley and Sons, 611 p. [p. 15-16].

Cole, L. A. and Alpert, I. A., 1922, Tidal bench marks, state of New York: U.S. Coast and Geodetic Survey Spec. Pub. 83, 175 p.

Coleman, A. P., 1936a, Lake Iroquois: Ontario Dept. of Mines, 45th Annual Rept., v. 45, pt. 7, p. 1-36.

________1936b, Geology of the north shore of Lake Ontario: Ontario Dept. of Mines, 45th Annual Rept., v. 45, pt. 7, p. 37-74.

Comstock, C. B.,1872, Irregular oscillations in surface of Lake Michigan, at Milwaukee: U. S. Chief of Eng. Ann. Rept.,1872, App. B., p. 1035-1040.

_______1873, Annual Report ...Survey of the Northern and Northwestern Lakes: U.S. Chief of Eng. Ann. Rept., 1873, App. BB., p. 1172-1173.

_______1875, Heights of lakes above tide: U.S. Chief of Eng. Ann. Rept., 1875, pt. 2, App. JJ., p. 853-854.

_______1876, Annual Report ...Survey of the Northern and Northwestern Lakes: U. S. Chief of Eng., 1876, pt. 3, App. HH., p. 5.

_______1882, Report upon the primary triangulation of the United States Lake Survey: U.S.A. War Dept. Engineers Prof. Paper no. 24, Washington, D.C., 925 p.

Conrad, Victor and Pollak, L. W., 1950, Methods in climatology: Cambridge, Mass., Harvard Univ. Press, 459 p.

Cooke, H. C., 1930, Studies of the physiography of the Canadian Shield. II. Glacial depression and post-glacial uplift: Royal Soc. Canada Trans., ser. 3, v. 24, p. 51-87.

_______1942, Is the land around Hudson Bay at present rising?: Am. Jour. Sci., v. 240, no. 2, p. 144-146.

Corbett, D. M. and others, 1943, Stream-gaging procedure: U.S. Geol. Survey Water-Supply Paper 888, 245 p.

Craig, B. G. and Fyles, J. G., 1961, Pleistocene geology of Arctic Canada, _in_ Geology of the Arctic, Proceedings of the first international symposium on arctic geology (Calgary, Alberta, Jan. 11-13, 1960), Vol. I: Toronto, Univ. of Toronto Press, p. 403-420.

Daly, R. A., 1934, The changing world of the Ice Age: New Haven, Conn., Yale Univ. Press, 271 p.

_______1940, Strength and structure of the earth: Prentice-Hall, Inc., 434 p.

De Geer, G. J., 1892a, On Pleistocene changes of level in eastern North America: Boston Soc. Nat. Hist. Proc., v. 25, p. 454-477.

________1892b, Quaternary changes of level in Scandinavia: Geol. Soc. Am. Bull., v. 3, p. 65-68.

Defant, Albert, 1958, Ebb and flow, the tides of earth, air and water: Ann Arbor, Mich., Univ. of Mich. Press, 121 p.

Deming, W. E., 1943, Statistical adjustment of data: New York, John Wiley and Sons, 261 p.

Dryden, H. L. and others, 1956, Hydrodynamics: New York, Dover Pubs., Inc., 634 p.

Dutton, C. E., 1892, On some of the greater problems of physical geology: Philos. Soc. Washington Bull., v. 11, p. 51-64.

Dwight, Timothy, 1822, Travels in New England and New York, vol. IV: New Haven, Conn., Timothy Dwight [Pub.], 527 p.

Eckhart, Carl, 1960, Hydrodynamics of oceans and atmospheres: New York, Pergamon Press, 290 p.

Ekman, V. W., 1902, Om jordrotationens inverkan på vindströmmar i hafvet: Nyt Magazin for Naturvidenskab [Kristiania], v. 40, no. 1, p. 37-63.

________1905-1906, On the influence of the earth's rotation on ocean-currents: Akiv for Math., Astron., och Fysik, v. 2, no. 11, p. 1-52.

Emmons, Ebenezer, 1837, First annual report of the second geological district of the state of New York: New York State Nat. Hist. Survey, Assembly Doc. no. 161, p. 97-150.

________1838, V. Report of E. Emmons, geologist of the 2d geological district of the state of New York; New York Nat. Hist. Survey, Assembly Doc. no. 200, p. 185-250.

Farrand, W. R., 1960, Former shorelines in western and northern Lake Superior basin: Michigan Univ., unpub. dissert. no. 5366, 226 p.

Ferrel, William, 1874, Report of meteorological effects on tides: U.S. Coast Survey Rept. of Superint., app. 6, p. 93-99.

Fischer, Irene, 1959, The impact of the ice age on the present form of the geoid: Am. Geophys. Union Trans., v. 64, no. 1, p. 85-87.

Fisher, R. A., 1954, Statistical methods for research workers, 12th ed.: New York, Hafner Pub. Co., 356 p.

Fleming, R. H. and Revelle, Roger, 1939, Physical processes in the ocean, in Recent marine sediments, a symposium: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 48-141.

Flint, R. F., 1947, Glacial geology and the Pleistocene Epoch: New York, John Wiley and Sons, 589 p.

______ 1957, Glacial and Pleistocene geology: New York, John Wiley and Sons, 553 p.

Fox, R. L., 1960, letter [U. S. Weather Bureau procedure for determining wind data]: Asheville, N. C., October 20, 1960, (typewritten and transcopy).

Francis, J. R., 1951, The aerodynamic drag of a free water surface: Royal Soc. [London] Proc., ser. A., v. 206, no. 1086, p. 387-406.

______ 1953, A note on the velocity distribution and bottom stress in a wind driven water current system: Jour. Marine Research, v. 12, no. 1, p. 93-98.

Freeman, J. R., 1926, Regulation of elevations and discharge of the Great Lakes: Chicago, Ill., Sanitary Dist. of Chicago, 548 p.

Gallé, P. H. 1925, On the relation between wind or current and mean sea level in the Indian and the Atlantic oceans and the adjacent seas: Koninkl. Akad. Wetensch. Amsterdam, sect. sci., v. 28, no. 10, p. 905-918.

Geol. Assoc. Canada, 1958, Glacial map of Canada: Toronto, Geol. Assoc. Canada.

______ 1950, Tectonic map of Canada: Toronto, Geol. Assoc. Canada.

Geol. Soc. America, 1949, Glacial map of America: New York, N. Y.

______ 1959, Glacial map of the U.S. east of the Rocky Mountains: New York, N. Y.

Gibbs, R. W., 1929, The adjustment of errors in practical science: London, Oxford Univ. Press, 112 p.

Gilbert, G. K., 1890, Lake Bonneville: U.S. Geol. Survey Mon. 1, 438 p.

________1896-97, Recent earth movement in the Great Lakes region: U.S. Geol. Survey 18th Ann. Rept., pt. 2-H, p. 595-647.

Gillies, D. K., 1959, Winds and water levels on Lake Erie: Great Lakes Research Div. Pub. no. 4, Mich. Univ. p. 35-42.

Goedicke, Victor, 1953, Introduction to the theory of statistics: New York, Harper and Bros. 286 p.

Goldthwait, J.W., 1908, A reconstruction of water planes of the extinct glacial lakes in the Lake Michigan basin: Jour. Geology, v. 16, p. 459-476.

Goodwin, H. M., 1920, Elements of the precision of measurements and graphical methods: New York, McGraw-Hill, 116 p.

Gossett, F. R., 1961, letter [U.S. Coast and Geodetic Survey elevations for bench mark Gristmill, Renssalaer, N. Y.]: Washington, D.C., Aug. 24, 1961. (Typewritten).

Graham, J. D., 1861, Investigation of the problem regarding the existence of a lunar tidal wave on the great fresh water lakes of North America: Am. Assoc. Adv. Sci. Proc., 14th meeting, Aug. 1860, p. 52-60.

Groves, G. W., 1957, Day to day variations of sea level: Meterol. Mon., v. 2, no. 10, p. 32-45.

Gutenberg, Beno, 1933, Tilting due to glacial melting: Jour. Geology, v. 41, no. 5, p. 449-467.

________1941, Changes in sea level, postglacial uplift, and mobility of the earth's interior: Geol. Soc. America Bull., v. 52, p. 721-72.

________1942, Is the land around Hudson Bay at present rising? Am. Jour. Sci., v. 240, no. 2, p. 147-149.

________1954, Postglacial uplift in the Great Lakes region: Archiv. Meteorol., Geophysik und Bioklimatologie, ser. A., v. 7, p. 243-251.

________1959, Physics of the earth's interior: New York, Academic Press, 240 p.

Hachey, H. B., 1952, Vertical temperature distribution in the Great Lakes: Canada Fish. Research Bd. Jour., v. 9, no. 7, p. 325-328.

Hall, James, 1843, Geology of New York, part IV: New York, Carroll and Cook, 683 p.

Harrington, M. W., 1895, Surface currents of the Great Lakes: U.S. Dept. of Agric., Weather Bur. Bull B, 14 p. and 5 charts.

Harris, R. A., 1907, Manual of tides: part V, currents, shallow-water tides, meteorological, and miscellaneous matters: U.S. Coast and Geodetic Survey Supt. Rept., app. 6, p. 231-545.

Harris, D. L., 1954, Wind tide and seiches in the Great Lakes, in Proceedings of fourth conference on coastal engineering (Chicago, Ill. Oct. 1953): Berkeley, Calif., Coun. on Wave Research, The Engineering Foundation, p. 25-51.

Haurwitz, B., 1951, The slope of lake surfaces under variable wind stresses: U. S. Army Corps of Eng., Beach Erosion Board Tech. Memo. No. 25, 23 p.

Hayford, J. F., 1899, Precise leveling in the United States: U. S. Coast and Geodetic Survey Supt. Rept. for 1898 to 1899, app. 8, 964 p. [1900].

________1903, Precise leveling in the United States, 1900-03, with a readjustment of the level net and resulting elevations: U.S. Coast and Geodetic Survey Supt. Dept., U.S. Senate Doc. 200, 58th Cong., 2nd. sess., app. 3, p. 189-809.

________1922, Effects of winds and of barometric pressures on the Great Lakes: Carnegie Inst. Washington Pub. 317, 133 p.

________1923, Winds and barometric effects on the Great Lakes: Eng. News-Record, v. 90, no. 15, April 12, 1923, p. 665-668.

Heiskanen, W. A. 1951, On the postglacial uplift of land in Fennoscandia: Am. Geophysics Union Trans., v. 32, p. 524-525.

Heiskanen, W. A. and Meinez, F.A.V., 1958, The earth and its gravity field: New York, McGraw-Hill, 470 p.

Hela, I., 1953, A study of land upheaval at the Finnish coast: Fennia, v. 76, no. 5, 38 p.

Hellström, Bo, 1941, Wind effect on lakes and rivers: Ingen. Vetensk. Acad. Handl. [Stockholm], no. 158, 191 p.

Hendricks, W. A., 1956, The mathematical theory of sampling: New Brunswick, N. J., The Scarecrow Press, 364 p.

Henry, A. J., 1902, Wind velocity and fluctuations of water level of Lake Erie: U.S. Weather Bur. Bull. J, no. 262, 22 p.

Herdan, Gustav, 1960, Small particle statistics: New York, Academic Press, 418 p.

Hobbs, W. H., 1911, The late glacial and postglacial uplift of the Michigan Basin: Mich. Geol. Survey, pub. 5, geol. ser. 3, p. 11-68.

________1935, Earth features and their meaning: New York, Macmillan Co., 517 p.

Holman, S. W., 1904, Discussion of the precision of measurements: New York, John Wiley and Sons, 176 p.

Holtzscherer, J. J. and Robin, G. De Q., 1954, Depth of polar ice caps: Geog. Jour., v. 120, p. 193-202.

Horton, R. E. and Grunsky, C. E., 1927, Hydrology of the Great Lakes: Chicago, Eng. Bd. of Review of Sanitary Dist. of Chicago, 432 p.

Hough, J. L., 1958, Geology of the Great Lakes: Urbana, Ill., Univ. of Ill. Press, 313 p.

Hubbard, Bela, 1840, Ancient Lake Ridge, in Third Annual Report of office of state geologist: Mich. House of Rep. No. 8, p. 102-108.

Humboldt, A. von, 1849, Cosmos, vol. I [Translated by E. C. Otté]: London, Henry G. Bohn, 372 p.

Hunt, I. A., Jr., 1958, Winds, wind set-ups, and seiches on Lake Erie, part 1: Second Natl. Conf. on Applied Meteorol., Eng. [Ann Arbor, Mich.], Sept. 10, 1958, 37 p.

Hutchinson, G. E., 1957, A treatise on limnology, vol. I: New York, John Wiley and Son, 1015 p.

Innes, M. J., 1960, Gravity and isostasy in northern Ontario and Manitoba: Dominion Observatory [Ottawa] Pub., v. 21, no. 6, p. 263-338.

Jamieson, T. F., 1865, History of the last geological changes in Scotland: Geol. Soc. London Quart. Jour., v. 21, p. 161-203.

_______ 1882, On the cause of the depression and re-elevation of the land during the Glacial Period: Geol. Mag. [Great Britain], new ser., decade 2, v. 9, p. 400-407, 457-466.

Jeffreys, Harold, 1940, Isostatic movement in Finland: Geog. Jour., v. 45, p. 384-385.

_______ 1959, The earth, its origin, history, and physical constitution, 4th ed.: Cambridge, Cambridge Univ. Press, 420 p.

Jensen, Henry and Sinding, Erik, 1945, On the differences between the heights of the mean sea-level at the self-recording tide-gauges at Korsør and Slipshavn: Geod. Inst. Medd. [Copenhagen], no. 20, 24 p.

Johnson, W. A., 1939, Recent changes of level of the land relative to sea level: Am. Jour. Sci., v. 237, no. 2, p. 94-98.

Kääriäinen, Erkki, 1953, On the recent uplift of the earth's crust in Finland: Fennia, v. 77, no. 2, 106p.

Keulegan, G. H., 1951, Wind tides in small closed channels: Natl. Bur. Standards Jour. Research, v. 46, no. 5, research pap. 2207, p. 358-381.

_______ 1953, Hydrodynamic effects of gales on Lake Erie: Natl. Bur. Standards Jour. Research, v. 50, no. 2, research pap. 2396, p. 99-109.

Kivisild, H. R., 1954, Wind effect on shallow bodies of water with special reference to Lake Okeechobee: Göteborg, Elanders Boktryckeri Aktiebolag [Kungl. Tekniske Högskolan (Stockholm)], 114 p.

Kuenen, Ph.H., 1950, Marine geology: New York, John Wiley and Sons, 568 p.

Lachlan, Major, 1855, On the periodical rise and fall of the Lakes: Am. Jour. Sci., ser. 2, v. 19, p. 60-70, 164-175; v. 20, p. 45-53.

Laidly, W. T., 1959, Regimen of the lakes and fluctuations of lake levels: Am. Assoc. Adv. Sci. Symposium on the Great Lakes Basin, Chicago, paper, Dec. 29-30, 1959, 7 p. (mimeographed).

Landsberg, H. E., 1960, Note on the recent climatic fluctuation in the United States: Am. Geophys. Union Jour. Geophys. Research, v. 65, no. 5, p. 1519-1525.

Langhaar, H. L., 1951, Wind tides in inland waters: Midwestern Conf. on Fluid Dynamics Proc., 1st. conf., sect. 4, no. 4, p. 278-296.

Langmuir, Irving, 1938, Surface motion of water induced by wind: Science, v. 87, no. 2250, p. 119-123.

Lawson, A. C., 1940, Isostatic control of fluctuations of sea level: Science, v. 92, no. 2382, p. 162-164.

Lee, H. A., Craig, B. G. and Fyles, J. G., Keewatin ice divide: Geol. Soc. Am., vol. 68, no. 12, pt. 2, p. 1760-1761 (Abstr.)

Leverett, Frank and MacLachlan, D. C., 1934, Variations in tilt lines in the Huron-Erie district: Science, v. 80, no. 2085, p. 550.

Leverett, Frank and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: U.S. Geol. Survey Mon. 53, 529 p.

Lougee, R. J., 1953, A chronology of postglacial time in eastern North America: Sci. Monthly, v. 76, no. 5, p. 259-276.

Lundell, G. E. and Hoffman, J. I., 1938, Outlines of methods of chemical analysis: New York, John Wiley and Sons, 250 p.

Lyell, Charles, 1837, Principles of Geology, 1st. American ed., vol. I: Philadelphia, Penn., James Kay, Jr. and Bro., 546 p.

________1838, Address to the Geological Society, delivered at the anniversary on the 17th of February: Geol. Soc. London Proc., v. 2, no. 49, p. 479-523.

________1844, On the ridges, elevated beaches, inland cliffs and boulder formations of the Canadian lakes and valley of St. Lawrence: Am. Jour. Sci. and Arts, v. 46, April 1844, p. 314-317.

Lyustikh, E. N., 1960, Isostasy and isostatic hypotheses: New York, Am. Geophys. Union, [originally pub. Trans. (TRUDY) Geophys. Inst. Acad. Sci. USSR, no. 38 (165), Moscow, 1957], 119 p.

MacLachlan, D. C., 1939, Warren shoreline in Ontario and in the Thumb of Michigan and its deformation: Mich. Univ. unpub. dissert. no. 1445, 89 p.

Marmer, H. A., 1931, Mean sea-level, in Figure of the Earth, Physics of the Earth II: Washington, D.C., Natl. Research Council, 286 p.

________1935, Tides and currents in New York Harbor: U.S. Coast and Geodetic Survey Spec. Pub. No. 111, 198 p.

________1948, Is the Atlantic Coast sinking? The evidence from the tide: Geog. Rev. v. 38, p. 652-657.

________1949, Sea level changes along coasts of the United States in recent years: Am. Geophys. Union Trans., v. 30, no. 2, p. 201-204.

________1951, Tidal datum planes: U.S. Coast and Geodetic Survey Spec. Pub. No. 135, [rev. (1951) ed.], 142 p.

Maskelyne, Nevil, 1775, An account of observations made on the mountain Schellien for finding its attraction: Royal Soc. London Phil Trans., abridged, v. 13, p. 702-720.

Mather, W. W., 1848, Notes and remarks connected with meteorology on Lake Superior and on the variations in its level by barometric causes, and variations in the season: Am. Jour. Sci., v. 6, p. 1-20.

Mather, J. R., 1954, The present climatic fluctuation and its bearing on a reconstruction of Pleisocene climatic conditions: Tellus, v. 6, no. 3, p. 287-301.

M'Culloch, J. R., 1845, M'Culloch's Universal Gazeteer, vol. I: New York, Harper and Bros., 1148 p.

Meinesz, F.A.V., 1937, The determination of the earth's plasticity from the post-glacial uplift of Scandinavia: isostatic adjustment: Koninkl. Akad. Wetensch. Amsterdam Proc. sect. Sci., v. 40, no. 8, p. 654-662.

________1954, Earth-crust movements in the Netherlands resulting from Fennoscandian postglacial isostatic readjustment and alpine foreland rising: Koninkl. Nederlandse Akad. Wetensch. Proc., ser. B.,v. 57, no. 7, p. 142-155.

Millar, F. G., 1952, Surface temperatures of the Great Lakes: Canada Fish. Research Bd. Jour., v. 9, no. 7, p. 329-376.

Miller, A. R., 1957, The effect of steady winds on sea level at Atlantic City: Meteorol. Mon., v. 2, no. 10, p. 24-31.

________1958, The effects of winds on water levels on the New England coast: Limnology and Oceanography, v. 3, no. 1, p. 1-14.

Mitchell, H. C., 1948, Definitions of terms used in geodetic and other surveys: U.S. Coast and Geodetic Survey Spec. Pub. No. 242, 87 p.

Montgomery R. B., 1952, The present position of the study of exchange across the ocean-atmosphere interface: International symposium on atmospheric turbulence in the boundry layer: U.S. Air Force Cambridge Research Center Geophys. Research Pap. No. 19, p. 131-140.

Moore, M. B., 1960, Theory and application of mechanical engineering measurements: New York, D. Van Nostrand Co., 296 p.

Moore, Sherman, 1922, Tilt of the earth in Great Lakes region: Military Engineer, v. 14, no. 75, p. 153-155, 181-183.

________1939, Marquette,[Michigan, gage history]: U. S. Lake Survey Archives [Detroit], file no. 3-3197, 6 p.

________1940a, Harbor Beach [Michigan gage history]: U.S. Lake Survey Archives [Detroit], file no. 3-3203, 7 p.

________1940b, Cleveland [Ohio, gage history]: U. S. Lake Survey Archives [Detroit], file no. 3-3213, 7 p.

________1941, Tibbetts Point [New York, gage history]: U.S. Lake Survey Archives [Detroit], file no. 3-3223, 3 p.

________1942a, Cape Vincent [New York, gage history]: U.S. Lake Survey Archives [Detroit], file no. 3-3223, 3 p.

________1942b, Buffalo [New York, gage history]: U.S. Lake Survey Archives [Detroit] file no. 3-3216, 7 p.

________1942c, Mackinaw [City, Michigan, gage history]: U. S. Lake Survey Archives [Detroit], file no. 3-3201, 3 p.

________1942D. Duluth-Superior [Minnesota, gage history]: U. S. Lake Survey Archives [Detroit], file no. 3-3194, 8 p.

________1942e, Port Arthur [Ontario, gage history]: U. S. Lake Survey Archives [Detroit] file no. 3-3192, 2 p.

________1943, Oswego [New York, gage history]: U. S. Lake Survey Archives [Detroit], file no. 3-3222, 7 p.

________1944a, Milwaukee (Popular St.) [Wisconsin gage history]: U.S. Lake Survey Archives [Detroit] file no. 3-3183, 8 p.

________1944b, Milwaukee (North Breakwater) [Wisconsin, gage history]: U.S. Lake Survey Archives [Detroit], file no. 3-3183, 2 p.

________1948, Crustal movement in the Great Lakes area: Geol. Soc. America Bull., v. 59, p. 697-710.

Murray, John, 1888, On the effects of winds on the distribution of temperature in the sea—and fresh-water lochs of the west of Scotland: Scottish Geog. Mag., v. 4, no. 7, p. 345-365.

________1908, The temperature of the fresh-water lochs of Scotland with special reference to Loch Ness: Royal Soc. Edinburgh Trans., v. 45, p. 407-489.

Nansen, Fridtjof, 1902, The currents of the North Polar Basin, and the influence of the wind upon the drift of the North Polar ice, in the Norwegian Polar Expedition, 1893-1896, scientific results, vol. III, pt. 3: London, Longmans, Green, and Co., p. 357-427.

________1904, The bathymetrical features of the North Polar Seas, in the Norwegian Polar Expedition, scientific results, vol. IV, sec. VIII: London, Longmans, Green, and Co., 232 p.

________1927, The earth's crust, its surface-forms, and isostatic adjustment: Norske Videnskapsakad.Oslo Avh., kl.I, no. 12, 121 p. [1928].

Németh, Ferenc, 1960, Variations in level and leveling data [abs.]: U.S. Geol. Survey Bull. 1116-A, 180-195 [Geophys. Abs. 180], p. 58.

Nevin, C. M., 1949, Principles of structural geology: New York, John Wiley and Sons, 410 p.

Newton, Isaac, 1728, A treatise of the system of the world: London, 154 p.

Niskanen, Erkki, 1939, On the upheaval of land in Fennoscandia: Acad. Sci. Fennicae Annales, ser. A, v. 53, 28 p. [1940].

________1943, On the deformation of the earth's crust under the weight of a glacial ice-load and related phenomena: Acad. Sci. Fennicae Annales, ser. A., pt. III, no. 7, 59 p.

________1949, On the elastic resistance of the earth's crust: Acad. Sci. Fennicae Annales, ser. A, pt. III, no. 21, 23 p.

Ortt, F. L., 1897, The effect of wind and atmospheric pressure on the tides: Nature, vol. 52, no. 1439, p. 80-84.

Panofsky, H. A. and Brier, G. W., 1958, Some applications of statistics to meteorology: Univ. Park, Penn., Penn. State Univ., 224 p.

Palmer, A. de F., 1912, The theory of measurements: New York, McGraw-Hill, 248 p.

Playfair, John, 1802, Illustrations of the Huttonian Theory of the earth: Edinburgh, William Creech [facsimile reprint, Urbana, Illinois, Univ. of Ill. Press, 1956], 528 p.

Pollak, M. J., 1957, Axial slope of sea level in Chesapeake Bay: Am. Geophys. Union Trans., v. 38, no. 1, p. 62-67.

________1960, Wind set-up and shear-stress coefficient in Chesapeake Bay: Am. Geophys. Union Jour. Geophys. Research, v. 65, no. 10, p. 3383-3389.

Powers, C. F., Jones, D. L., and Ayers, J. C., 1959, Sources of hydrographic and meteorological data on the Great Lakes: U.S. Fish and Wildlife Service Rept.—Fish. No. 4, 183 p.

Pratt, J. H., 1855, On the attraction of the Himalaya Mountains, and of the elevated regions beyond them, upon the plumb line in India: Royal Soc. London Phil. Trans., v. 145, pt. 1, p. 53-100.

________1859, On the deflection of the plumb line in India caused by the attraction of the Himalaya Mountains and of the elevated region beyond; and its modification by the compensating effect of a deficiency of matter below the mountain mass: Royal Soc. London. Phil. Trans., v. 149, pt. 2, p. 745-778.

Prest, V. K., 1957, Pleistocene geology and superficial deposits, <u>in</u> Geology and economic minerals of Canada: Canada Geol. Survey Econ. Geol. Ser. no. 1 (4th ed.), p. 443-495.

Price, C. A., 1954, Crustal movement in the Lake Ontario-Upper St. Lawrence River Basin: Ottawa, Dept. of Mines and Tech. Surveys, 5 p. and 20 pl.

Proudman, Joseph, 1953, Dynamical oceanography: London, Methuen and Co., 409 p.

________1954, Tides, in Encyclopaedia Britannica, vol. 22: Chicago, Encycl. Brit., Inc., p. 193-205.

Rainsford, H. F., 1957, Survey adjustments and least squares: London, Constable and Co., 326 p.

Rappleye, H. S., 1948a, Manual of geodetic leveling: U.S. Coast and Geodetic Survey Spec. Pub. no. 239, 94 p.

________1948b, Manual of leveling computation and adjustment: U.S. Coast and Geodetic Survey Spec. Pub. no. 240, 178 p.

Renqvist, Henrik, 1952, Endogenetic phenomena, in Suomi, a general handbook on the geography of Finland: Fennia, v. 72, 626 p.

Robinson, H. H., 1908, Ancient water-planes and crustal deformation: Jour. Geology, v. 16, no. 4, p. 347-356.

Ropes, G. E., 1960, letter [U. S. Lake Survey conversion factors for changing 1903 datum to 1935 datum]: Detroit, Mich., Aug. 12, 1960.

Rune, G. A., 1950, Report of some in Sweden observed irregularities in the Fenno-Scandian post-glacial upheaval of land: Bull. Géod., new ser., no. 18, Dec. 1, 1950, p. 436-437.

Saurmo, M., 1939, The mode of the land upheaval in Fennoscandia during the late Quaternary time: Fennia, v. 66, no. 2, 26 p.

Saville, T., Jr., 1952, Wind set-up and waves in shallow water: U.S.A. Corps of Eng., Beach Erosion Bd. Tech. Memo., No. 27, 36 p.

Schureman, Paul, 1949, Tide and current glossary: U.S. Coast and Geodetic Survey Spec. Pub. No. 228, rev. (1949) ed., 40 p.

Shaler, N. S., 1868, On the nature of movement involved in the changes of level of shore lines: Boston Soc. Nat. Hist. Proc., v. 12, p. 128-136.

Sharp, R. P., 1953, Shorelines of the Glacial Great Lakes in Cook County, Minnesota: Am. Jour. Sci., v. 251, no. 2, p. 109-139.

Shewhart, W. A., 1939, Statistical method from the viewpoint of quality control: Washington, D.C., U.S. Dept. of Agri. Grad. School, 155 p.

Simonsen, O., 1949, Nivellements-nul paa Sjaelland, Møn og Lolland-Falster med saerligt henblik paa København og Frederiksberg, 1845-1946 [On level-data in Zealand, Møn, and Lolland-Falster with special reference to Copenhagen and Frederiksberg, 1845-1945]: Copenhagen, Geod. Inst., 182 p. [English summary p. 144-153].

Sirén, Allan, 1951, On computing the land uplift from the lake water level records in Finland: Fennia, v. 73, no. 5, 182 p.

Spencer, J. W., 1890, The deformation of Iroquois beach and birth of Lake Ontario: Am. Jour. Sci., ser. 3, v. 40, p. 443-451.

________1894, The duration of Niagara Falls: Am. Jour. Sci., ser. 3, v. 48, p. 455-472.

________1907, The fall of Niagara: Ottawa, Canada Geol. Survey, 490 p.

________1913, Postglacial earth movements about Lake Ontario and the St. Lawrence River: Geol. Soc. America Bull., v. 24, p. 217-228.

Stevens, J. C., 1919-20, The accuracy of water level recorders: Am. Soc. Civil Eng. Trans., v. 83, [paper no. 1444], p. 894-903.

________no date, Hydrographic data book: Portland, Oregon, Leupold and Stevens Instruments, Inc., 118 p.

Stodder, (unknown), 1851, Meeting of Nov. 20, 1850: Boston Soc. Nat. Hist. Proc., v. 3, p. 359.

Stommel, Henry, 1960, The Gulf Stream: Berkeley, Univ. of Calif. Press, 202 p.

Stuntz, G. R.,1869, On some recent geological changes in northeastern Wisconsin: Am. Assoc. Adv. Sci. Proc., 18th meet., v. 18, p. 205-210.

Sverdrup, H. U., Johnson, M. W. and Fleming, R. H., 1942, The oceans: their physics, chemistry, and general biology: New York, Prentice-Hall, 1087 p.

Taylor, F. B., 1927, The present and recent rate of land-tilting in the region of the Great Lakes: Mich. Acad. Sci. Papers, v. 7, p. 145-157.

Thomas, M. K., 1961, letter [summer temperatures and barometric pressures for Toronto and Trenton, Ont. (1948-1959)]: Toronto, Ontario, Canada Meterol. Div., Mar. 24, 1961.

Thorarinsson, Sigurdur, 1940, Present glacier shrinkage and eustatic changes of sea-level: Geol. Annaler, v. 22, no. 3-4, p. 131-159.

Tsuboi, Chuji, 1939, Deformations of the earth's crust as disclosed by geodetic measurements: Gerlands Beitr. Geophysik, Ergebnisse der Kosmischen physik, v. 4, p. 106-168.

Tyrrell, J. B., 1896, Is the land around Hudson Bay at present rising? Am. Jour. Sci., ser. 4, v. 2, no. 9, p. 200-205.

________ 1897, Report on the Doobaunt, Kazan and Ferguson Rivers and the northwest coast of Hudson Bay: Canada Geol. Survey Ann. Rept. (new series), v. 9, pt. F, no. 618, 218 p.

U.S. Bureau of Reclamation, 1953, Water measurement manual: Denver, Colo. 271 p.

U.S. Coast and Geodetic Survey, 1960, Geodetic operations [U.S. Natl. Rept. 1957-1959]: Am. Geophys. Union Trans., v. 41, no. 2, p. 131-143.

U.S. Deep Waterways Comm., 1897, Report of the United States Deep Waterways Commission: U.S. 54th Cong., 2d sess., House Doc. No. 192, 263 p.

U.S. Geological Survey, 1958, Suggestions to authors of the reports of the United States Geological Survey, 5th ed.: Washington, D.C., U.S. Govt. Printing Office, 255 p.

U.S. Lake Survey, no date, Monthly and annual lake surface elevations for Lakes Erie, Ontario, and Superior: Detroit, Michigan [1950-1959] (mimeographed).

________ 1949, Great Lakes datum planes: Military Eng., v. 41, no. 284, p. 459-460.

________ 1950, Levels of the Great Lakes: Military Eng., v. 42, no. 288, p. 302-303.

________ 1951a, Vertical control on the Great Lakes: Military Eng., v. 43, no. 291, p. 58

________1951b, Crustal movement of the earth in the Great Lakes region: Military Eng., v. 43, no. 293, p. 213-214.

________1955, Great Lakes diversions and works of man: Military Eng., v. 47, no. 318, p. 297.

________1956, Crustal movement in the Great Lakes region: Military Eng., v. 48, no. 325, p. 388.

________1957, Secular variations for Great Lakes levels: Military Eng., v. 49, no. 327, p. 50.

U.S. Weather Bureau, 1950-1959a, Climatological Data, National Summary: Asheville, N.C., Vols. 1-10 [data for Toledo, Ohio and Buffalo, New York].

________1950-1959b, Local climatological data: Asheville, North Carolina, National Weather Records Center.

________1950-1959c, Local climatological data supplements: Asheville, North Carolina, National Weather Records Center.

________1959, Climatology and weather services of the St. Lawrence Seaway and Great Lakes: Tech. Pap. no. 35, Washington, D.C., 75 p.

Upham, Warren, 1895, Late glacial or Champlain subsidence and re-elevation of the St. Lawrence River Basin: Minn. Geol. and Nat. Hist. Survey 23rd. Ann. Rept. (1894), p. 156-193.

Van Dorn, W. G., 1953, Wind stress on an artificial pond: Jour. Marine Research, v. 12, no. 3, p. 249-276.

Wallis, W. A. and Roberts, H. V., 1956, Statistics, a new approach: Glencoe, Ill., The Free Press, 646 p.

Wedderburn, E. M. and Watson, W., 1908-09. Observations with a current meter in Loch Ness: Royal Soc. Edinburgh Proc., v. 29, p. 619-647.

Wedderburn, W. S., 1909-10, Current observations in Loch Gary: Royal Soc. Edinburgh Proc., v. 30, p. 312-323.

Wheeler, L. L. and Lehnartz, F. W., 1876, Leveling operations: U.S. Army Chief of Eng. Ann. Rept., 1876, pt. 3, app. F., p. 70-76.

Whitten, C. A., 1958, Distortion in continental triangulation: Am. Geophys. Union Trans., v. 39, no. 3, p. 536 [Abs.].

Whittlesey, Charles, 1838, Mr. Whittlesey's report: Ohio Geol. Survey 2nd Ann. Rept., Columbus, Ohio, p. 41-71.

________1859, Fluctuations of level in the North American Lakes: Smithsonian contrib. to knowledge, vol. 12, Washington, 25 p. [1860].

Williams, M. Y., 1949, Churchill, Manitoba: Canada. Geog. Jour., v. 39, no. 3, p. 122-133.

Wilson, B. W., 1960, Note on surface wind stress over water at low and high wind speeds: Am. Geophys. Union Jour. Geophys. Research, v. 65, no. 10, p. 3377-3382.

Wilson, J. Tuzo, 1950, Recent applications of geophysical methods to the study of the Canadian Shield: Am. Geophys. Union Trans., v. 31, no. 1, p. 101-114.

Wright, T. W. and Hayford, J. F., 1906, The adjustment of observations by the method of least squares with application to geodetic work; New York, D. Van Nostrand Co., 2nd ed., 298 p.

Young, R. K., 1929, Tides and seiches on Lake Huron: Royal Astron, Soc. Canada Jour., v. 23, p. 445-455.

Zach, Baron de, 1814, L'attraction des montagnes et ses effects sur les fils a plomb ou sur les niveaux des instruments d'astronomie: vol. 1: Avignon, Chez Sequin Ainé imprimeur-libaire, p. v-xvi, 1-28. [Franz Xaver freiherr von].

# APPENDIX I

Photostat of

<u>Report upon</u>

<u>The Primary Triangulation</u>

<u>of the</u>

<u>United States Lake Survey</u>

(Comstock, C. B., 1882, p. 595)

showing fundamental assumption underlying water-leveling and the determination of rates of uplift on the Great Lakes.

# CHAPTER XXII.

## ELEVATIONS OF THE GREAT LAKES.

§ **1.** The elevations of the Great Lakes above mean tide sea-level, as determined by the Lake Survey, depend upon two distinct processes, viz., that of spirit-level measurements and that of water-level measurements.

By the first process, starting from a bench-mark of known height above sea-level at Greenbush, New York, the elevation of a bench-mark at Oswego, New York, near the east end of Lake Ontario, was found. In like manner the differences in elevation of bench-marks at the following pairs of points were determined: Port Dalhousie, Ontario, near the west end of Lake Ontario, and Port Colborne, Ontario, near the east end of Lake Erie; Rockwood, Michigan, near the west end of Lake Erie, and Lakeport, Michigan, near the south end of Lake Huron; Escanaba, Michigan, near the north end of Green Bay,* and Marquette, Michigan, on the south shore of Lake Superior.

By the second process, depending on the assumption that the mean surface of each lake is level, the relative heights of the pairs of bench-marks for the respective lakes were determined. For this purpose water-gauges were fixed near these bench-marks, and tri-daily observations of the height of the water-surface at each gauge were made during the months of May, June, July, and August, 1875, this series of observations being taken as of sufficient extent to give a reliable mean. Assuming, then, that the mean surface of each lake for this period of about four months was level, the differences of the gauge-readings gave the relative heights of the zero-points of the two gauges on each lake, and as these zero-points were carefully referred to the corresponding bench-marks, the relative heights of these bench-marks were also known.

As the surfaces of the lakes vary considerably in elevation from year to year, their mean elevations can only be found by observations extending over a series of years. Such observations, consisting of tri-daily gauge-readings, have been made on Lake Ontario at Charlotte and Sacket's Harbor, N. Y.; on Lake Erie at Cleveland, Ohio, and Erie, Pa.; on Lake Huron at Port Austin, Mich.; on Lake Michigan at Milwaukee, Wis.; and on Lake Superior at Marquette, Mich. By comparing the observations made at Oswego in 1875 with those made during the same time at Charlotte, the elevation of the bench-mark at the latter place, to which the surface of Lake Ontario has been referred, becomes known, and thus also the mean elevation of Lake Ontario for the period covered by the observations at Charlotte. Similarly the mean elevation of Lake Erie has been derived from the observations made at Cleveland, the mean elevation of Lakes Huron and Michigan from the observations made at Milwaukee, and the mean elevation of Lake Superior from the observations made at Marquette.

The methods used and the results derived thereby, of which the foregoing is a brief outline, will now be given somewhat in detail.

### LEVELING BY MEANS OF THE SPIRIT-LEVEL.

§ **2.** For this work two parties were detailed, Assistant F. W. Lehnartz having charge of the first, and Assistant L. L. Wheeler of the second. During the year 1875 the lines from Greenbush to Oswego, and from Port Dalhousie to Port Colborne were leveled in duplicate, and a single line of levels was run from Gibraltar, near Rockwood, Mich., to Lakeport. The instruments used during this year were Stackpole level No. 1496, 11 inches focal length, object-glass 1¼ inches in

* For reasons given in the sequel it is assumed that Lakes Huron and Michigan and Green Bay have the same altitude.

## APPENDIX II

Table of "hindcast" for Lake Erie.

Tables of Lake Erie vector wind velocities - 1950-59.

Tables of Lake Ontario vector wind velocities - 1948-55.

Tables of Lake Superior vector wind velocities - 1950-59.

Table of Lake Erie over-water effective wind velocities (linear).

Procedure for computing barometric pressure effect.

Table of Lake Erie barometric pressure effects - 1950-59.

Table of Lake Ontario barometric pressure effects - 1948-55.

Table of Lake Erie gage differences vs. effective wind velocity squared (linear function).

Table of Lake Erie gage differences vs. effective wind velocity squared (cosine function).

TABLE 6

LAKE ERIE GAGE DIFFERENCE "HINDCAST"—WINDS FROM 23° RIGHT OF TOLEDO-BUFFALO AXIS

| Year | Wind Velocity | | | Effective Velocity Squared ($V^2$) | Calculated Wind Slope | Barometric Pressure Effect | Gage Differences | |
|---|---|---|---|---|---|---|---|---|
| | From | | mph | | | | Calculated | Observed |
| 1950 | 223° | (SSW) | 387 | 8300 | -0.1505 | +0.015 | -0.1355 = -0.14 | -0.14 |
| 1951 | 224° | (SW) | 518 | 15400 | -0.0617 | -0.007 | -0.0687 = -0.07 | -0.05 |
| 1952 | 214.5° | (SW) | 576 | 14900 | -0.0690 | -0.009 | -0.0770 = -0.08 | -0.08 |
| 1953 | 223° | (SW) | 505 | 14200 | -0.0766 | +0.002 | -0.0746 = -0.08 | -0.10 |
| 1954 | 235.5° | (SW) | 592 | 18500 | -0.0230 | +0.010 | -0.0130 = -0.01 | -0.02 |
| 1955 | 227° | (SW) | 304 | 5600 | -0.1843 | -0.010 | -0.1943 = -0.19 | -0.22 |
| 1956 | 227.5° | (SW) | 582 | 20700 | -0.0045 | -0.001 | +0.0035 = 0.00 | +0.01 |
| 1957 | 233° | (SW) | 559 | 17400 | -0.0367 | +0.003 | -0.0337 = -0.03 | -0.02 |
| 1958 | 240° | (WSW) | 735 | 25300 | +0.0620 | -0.019 | +0.0430 = +0.04 | +0.03 |
| 1959 | 237° | (SW) | 559 | 10000 | -0.1293 | +0.015 | -0.1143 = -0.11 | -0.12 |

Notes:
(1) Gage difference = wind slope + barometric pressure effect.
(2) Wind slope computed from 23° regression line (wind slope = $1.250 \times 10^{-5} V^2 - 0.2543$).
(3) June 1950 wind estimated from an average of Toledo and Buffalo June winds from 1951-59 (winds from years with low observed gage differences weighted double).
(4) September 1957 wind for Toledo estimated by averaging the September Toledo winds for 1951-54, 56, and 58 (the years with low observed gage differences were not included in the average).

TABLE 7

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1950

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | WSW | 10 | ENE | 2 | WSW | 10 | ENE | 11 | WSW | 12 | ENE | 4 | WSW | 16 | ENE | 18 |
| 2 | SSW | 15 | SW | 14 | WSW | 10 | NE | 9 | SSW | 17 | SW | 22 | WSW | 16 | NE | 14 |
| 3 | SW | 7 | WSW | 4 | W | 11 | WNW | 1 | SW | 8 | WSW | 6 | W | 18 | WNW | 2 |
| 4 | W | 11 | SW | 6 | WNW | 3 | N | 10 | W | 11 | SW | 9 | WNW | 6 | N | 16 |
| 5 | WSW | 13 | NNW | 4 | N | 6 | NE | 7 | WSW | 5 | NNW | 7 | N | 10 | NE | 11 |
| 6 | SW | 15 | NW | 6 | N | 5 | ENE | 6 | SW | 17 | NW | 10 | N | 8 | ENE | 10 |
| 7 | SSW | 8 | E | 2 | ESE | 2 | ENE | 7 | SSW | 9 | E | 3 | ESE | 4 | ENE | 11 |
| 8 | SSE | 7 | ESE | 4 | SE | 2 | NE | 8 | SSE | 8 | ESE | 5 | SE | 3 | NE | 13 |
| 9 | S | 9 | ENE | 6 | SW | 6 | ENE | 6 | S | 10 | ENE | 10 | SW | 11 | ENE | 9 |
| 10 | WSW | 13 | ENE | 7 | WSW | 4 | N | 3 | WSW | 15 | ENE | 12 | WSW | 7 | N | 5 |
| 11 | WNW | 4 | WSW | 2 | S | 5 | ESE | 2 | WNW | 5 | WSW | 2 | S | 8 | ESE | 4 |
| 12 | SSW | 11 | SSW | 8 | NE | 4 | E | 6 | SSW | 12 | SSW | 14 | NE | 7 | E | 9 |
| 13 | S | 10 | W | 12 | NE | 6 | WSW | 8 | S | 11 | W | 18 | NE | 10 | WSW | 13 |
| 14 | N | 4 | NE | 4 | ESE | 5 | W | 11 | N | 5 | NE | 7 | ESE | 8 | W | 18 |
| 15 | SSE | 5 | SSE | 7 | S | 4 | W | 8 | SSE | 6 | SSE | 11 | S | 6 | W | 13 |
| 16 | WSW | 9 | SSW | 15 | SSW | 5 | NNW | 4 | WSW | 10 | SSW | 24 | SSW | 8 | NNW | 7 |
| 17 | N | 10 | SW | 15 | WSW | 7 | NE | 4 | N | 11 | SW | 24 | WSW | 11 | NE | 6 |
| 18 | E | 6 | WNW | 6 | NE | 10 | SW | 7 | E | 7 | WNW | 10 | NE | 16 | SW | 12 |
| 19 | NE | 1 | E | 14 | WNW | 6 | NE | 4 | NE | 1 | E | 22 | WNW | 10 | NE | 6 |
| 20 | WSW | 10 | NE | 12 | NW | 4 | ENE | 8 | WSW | 11 | NE | 20 | NW | 7 | ENE | 13 |
| 21 | NW | 1 | NE | 10 | WSW | 5 | E | 12 | NW | 1 | NE | 16 | WSW | 8 | E | 19 |
| 22 | S | 10 | E | 3 | SSW | 10 | NNW | 5 | S | 11 | E | 6 | SSW | 15 | NNW | 8 |
| 23 | SSW | 14 | NW | 7 | SSW | 10 | NNW | 7 | SSW | 16 | NW | 12 | SSW | 15 | NNW | 11 |
| 24 | WSW | 8 | WSW | 8 | SSW | 8 | NW | 7 | WSW | 9 | WSW | 12 | SSW | 12 | NW | 11 |
| 25 | NE | 2 | W | 7 | WSW | 2 | SW | 13 | NE | 2 | W | 11 | WSW | 4 | SW | 21 |
| 26 | WSW | 8 | NW | 3 | NE | 4 | SW | 8 | WSW | 9 | NW | 5 | NE | 7 | SW | 12 |
| 27 | WNW | 12 | WSW | 5 | SSW | 8 | SSE | 4 | WNW | 14 | WSW | 8 | SSW | 13 | SSE | 7 |
| 28 | SW | 8 | W | 4 | SSW | 8 | S | 5 | SW | 9 | W | 6 | SSW | 12 | S | 8 |
| 29 | WNW | 10 | SW | 7 | SW | 5 | SSE | 6 | WNW | 11 | SW | 11 | SW | 8 | SSE | 9 |
| 30 | SW | 8 | SW | 8 | ENE | 7 | SSW | 4 | SW | 9 | SW | 14 | ENE | 11 | SSW | 6 |
| 31 | | | SSW | 6 | E | 1 | | | | | SSW | 10 | E | 2 | | |
| Monthly Vector Resultant | SW | 163 | SW | 58 | SW | 66 | NE | 36 | SW (231°) | 198 | SW (234°) | 92 | SW (232°) | 106 | NE (34°) | 55 |
| Daily Vector Mean | SW | 5.4 | SW | 2 | SW | 2 | NE | 1 | SW | 6.6 | SW | 2.8 | SW | 3.4 | NE | 1.8 |

TABLE 8

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1951

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SSW | 9 | W | 9 | N | 9 | NNE | 11 | SSW | 14 | W | 15 | N | 14 | NNE | 18 |
| 2 | ENE | 4 | WSW | 6 | SSW | 5 | NNE | 5 | ENE | 6 | WSW | 10 | SSW | 8 | NNE | 8 |
| 3 | WSW | 6 | S | 7 | NNW | 5 | NNE | 6 | WSW | 10 | S | 11 | NNW | 8 | NNE | 9 |
| 4 | NW | 6 | SW | 14 | NNE | 7 | NNE | 2 | NW | 10 | SW | 22 | NNE | 12 | NNE | 3 |
| 5 | NNE | 5 | NW | 17 | NE | 2 | E | 4 | NNE | 8 | NW | 27 | NE | 4 | E | 6 |
| 6 | ENE | 2 | NW | 5 | SSE | 4 | WSW | 11 | ENE | 4 | NW | 8 | SSE | 7 | WSW | 18 |
| 7 | E | 12 | SSW | 8 | W | 5 | WNW | 9 | E | 18 | SSW | 12 | W | 8 | WNW | 14 |
| 8 | ENE | 10 | SSW | 12 | SW | 6 | WSW | 3 | ENE | 17 | SSW | 20 | SW | 10 | WSW | 5 |
| 9 | WSW | 6 | WSW | 7 | NW | 4 | ESE | 6 | WSW | 9 | WSW | 12 | NW | 6 | ESE | 10 |
| 10 | NW | 9 | SSW | 3 | NNE | 4 | S | 12 | NW | 15 | SSW | 5 | NNE | 7 | S | 20 |
| 11 | NNW | 5 | NE | 7 | E | 4 | SSW | 14 | NNW | 8 | NE | 11 | E | 7 | SSW | 22 |
| 12 | E | 7 | N | 6 | WNW | 5 | S | 10 | E | 12 | N | 10 | WNW | 8 | S | 17 |
| 13 | N | 6 | NE | 6 | WSW | 3 | SW | 7 | N | 9 | NE | 10 | WSW | 4 | SW | 11 |
| 14 | NNW | 3 | ENE | 5 | WNW | 6 | SSW | 8 | NNW | 5 | ENE | 8 | WNW | 10 | SSW | 13 |
| 15 | SE | 1 | W | 2 | SSW | 8 | WSW | 8 | SE | 2 | W | 4 | SSW | 13 | WSW | 13 |
| 16 | SSE | 4 | WSW | 6 | NW | 6 | WSW | 7 | SSE | 7 | WSW | 10 | NW | 10 | WSW | 12 |
| 17 | ENE | 6 | NE | 11 | NE | 6 | SW | 6 | ENE | 9 | NE | 18 | NE | 9 | SW | 9 |
| 18 | SSW | 6 | WSW | 1 | | 0 | WSW | 4 | SSW | 10 | WSW | 2 | | 0 | WSW | 6 |
| 19 | SW | 8 | WNW | 8 | WSW | 6 | SW | 6 | SW | 14 | WNW | 13 | WSW | 9 | SW | 9 |
| 20 | SW | 12 | WNW | 6 | SSW | 4 | S | 10 | SW | 20 | WNW | 10 | SSW | 6 | S | 15 |
| 21 | NE | 6 | SSW | 14 | WNW | 14 | SSW | 15 | NE | 9 | SSW | 22 | WNW | 22 | SSW | 24 |
| 22 | SSE | 4 | SW | 6 | NW | 7 | WSW | 11 | SSE | 6 | SW | 10 | NW | 11 | WSW | 18 |
| 23 | W | 5 | NE | 6 | N | 4 | SW | 9 | W | 8 | NE | 7 | N | 6 | SW | 14 |
| 24 | SW | 12 | ESE | 3 | NNE | 5 | SW | 6 | SW | 19 | ESE | 5 | NNE | 8 | SW | 9 |
| 25 | NE | 7 | SW | 3 | E | 4 | NNW | 2 | NE | 11 | SW | 5 | E | 6 | NNW | 4 |
| 26 | SSW | 8 | SW | 6 | SSE | 5 | SE | 10 | SSW | 13 | SW | 9 | SSE | 8 | SE | 16 |
| 27 | WSW | 5 | WSW | 8 | S | 6 | WSW | 22 | WSW | 8 | WSW | 14 | S | 10 | WSW | 34 |
| 28 | SW | 5 | NNE | 6 | ESE | 2 | W | 10 | SW | 8 | NNE | 10 | ESE | 3 | W | 15 |
| 29 | W | 5 | ENE | 4 | ESE | 2 | NE | 2 | W | 8 | ENE | 7 | ESE | 4 | NE | 4 |
| 30 | WSW | 6 | S | 1 | SE | 6 | SSE | 7 | WSW | 10 | S | 2 | SE | 10 | SSE | 11 |
| 31 | | | SW | 7 | SSW | 11 | | | | | SW | 11 | SSW | 18 | | |
| Monthly Vector Resultant | SW | 32 | WSW | 74 | W | 31 | SW | 134 | SW | (235°) 54 | WSW | (252°) 124 | W | (281°) 54 | SW | (220°) 214 |
| Daily Vector Mean | SW | 1.1 | WSW | 2.4 | W | 1 | SW | 4.5 | SW | 1.8 | WSW | 4 | W | 1.7 | SW | 7.1 |

TABLE 9

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1952

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNE | 6 | E | 12 | ESE | 3 | SSW | 9 | NNE | 6 | E | 19 | ESE | 5 | SSW | 14 |
| 2 | SW | 7 | S | 7 | W | 2 | W | 7 | SW | 8 | S | 11 | W | 4 | W | 11 |
| 3 | WSW | 8 | SW | 13 | ENE | 11 | W | 8 | WSW | 8 | SW | 21 | ENE | 18 | W | 13 |
| 4 | NE | 9 | WNW | 8 | SW | 11 | SW | 4 | NE | 10 | WNW | 13 | SW | 18 | SW | 7 |
| 5 | S | 4 | ENE | 9 | NW | 3 | S | 4 | S | 4 | ENE | 15 | NW | 5 | S | 6 |
| 6 | W | 10 | E | 9 | ENE | 6 | WSW | 2 | W | 11 | E | 14 | ENE | 9 | WSW | 2 |
| 7 | NW | 6 | S | 6 | NE | 5 | NE | 11 | NW | 6 | S | 10 | NE | 7 | NE | 18 |
| 8 | SW | 10 | SW | 10 | ENE | 3 | ENE | 4 | SW | 11 | SW | 16 | ENE | 5 | ENE | 6 |
| 9 | W | 11 | NNW | 9 | S | 8 | SSW | 2 | W | 13 | NNW | 14 | S | 12 | SSW | 3 |
| 10 | W | 16 | SSE | 1 | WNW | 12 | SSW | 1 | W | 18 | SSE | 2 | WNW | 20 | SSW | 2 |
| 11 | NNW | 8 | SSW | 9 | SW | 4 | SE | 3 | NNW | 8 | SSW | 15 | SW | 6 | SE | 4 |
| 12 | ENE | 2 | SW | 9 | NNE | 7 | ESE | 4 | ENE | 3 | SW | 14 | NNE | 11 | ESE | 6 |
| 13 | E | 8 | S | 8 | NNW | 3 | SE | 3 | E | 9 | S | 14 | NNW | 5 | SE | 5 |
| 14 | SSW | 5 | SW | 12 | S | 6 | SSW | 10 | SSW | 6 | SW | 19 | S | 10 | SSW | 16 |
| 15 | ENE | 4 | W | 12 | SSW | 8 | W | 10 | ENE | 5 | W | 19 | SSW | 13 | W | 15 |
| 16 | SSW | 8 | SSE | 3 | WSW | 10 | WSW | 10 | SSW | 8 | SSE | 5 | WSW | 17 | WSW | 16 |
| 17 | W | 8 | SW | 7 | WNW | 4 | S | 4 | W | 9 | SW | 10 | WNW | 7 | S | 6 |
| 18 | WSW | 12 | WSW | 6 | NW | 4 | SSW | 9 | WSW | 13 | WSW | 10 | NW | 6 | SSW | 14 |
| 19 | NW | 8 | W | 8 | ENE | 5 | WNW | 9 | NW | 9 | W | 13 | ENE | 8 | WNW | 15 |
| 20 | NE | 7 | SW | 10 | S | 5 | W | 6 | NE | 8 | SW | 16 | S | 8 | W | 10 |
| 21 | ENE | 12 | SW | 12 | W | 4 | W | 8 | ENE | 13 | SW | 19 | W | 6 | W | 13 |
| 22 | NE | 10 | WSW | 8 | NE | 10 | SW | 3 | NE | 11 | WSW | 12 | NE | 16 | SW | 5 |
| 23 | SW | 5 | W | 13 | NNE | 6 | W | 6 | SW | 6 | W | 20 | NNE | 10 | W | 10 |
| 24 | SW | 14 | NW | 6 | E | 4 | SSW | 4 | SW | 15 | NW | 9 | E | 6 | SSW | 6 |
| 25 | SW | 14 | S | 5 | ESE | 2 | SSW | 10 | SW | 16 | S | 8 | ESE | 3 | SSW | 16 |
| 26 | WSW | 4 | SSW | 9 | ESE | 2 | WSW | 2 | WSW | 4 | SSW | 14 | ESE | 3 | WSW | 3 |
| 27 | ENE | 7 | NW | 2 | SE | 4 | SSW | 4 | ENE | 8 | NW | 4 | SE | 6 | SSW | 6 |
| 28 | ENE | 10 | SW | 5 | E | 8 | SSW | 10 | ENE | 11 | SW | 8 | E | 12 | SSW | 16 |
| 29 | E | 3 | N | 6 | SSE | 2 | SW | 6 | E | 3 | N | 9 | SSE | 2 | SW | 9 |
| 30 | ENE | 18 | WSW | 8 | E | 7 | ENE | 6 | ENE | 20 | WSW | 14 | E | 11 | ENE | 10 |
| 31 | | | NE | 6 | SSE | 9 | | | | | NE | 10 | SSE | 15 | | |
| Monthly Vector Resultant | W | 44 | SW | 125 | ESE | 24 | SSW | 76 | W (272°) | 43 | SW (230°) | 200 | SE (130°) | 31 | SW (228°) | 157 |
| Daily Vector Mean | W | 1.1 | SW | 4.0 | ESE | 0.8 | SSW | 2.5 | W | 1.4 | SW | 6.4 | SE | 1.0 | SW | 5.2 |

TABLE 10

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1953

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNE | 10 | W | 2 | SW | 2 | SW | 5 | NNE | 11 | W | 2 | SW | 3 | SW | 8 |
| 2 | NW | 6 | SW | 12 | NNW | 2 | SW | 3 | NW | 7 | SW | 18 | NNW | 2 | SW | 5 |
| 3 | SSW | 5 | N | 6 | E | 9 | SSW | 4 | SSW | 6 | N | 9 | E | 14 | SSW | 7 |
| 4 | SSW | 11 | SE | 4 | SW | 9 | SW | 8 | SSW | 12 | SE | 7 | SW | 15 | SW | 12 |
| 5 | SW | 18 | SSW | 5 | NNE | 8 | WSW | 7 | SW | 20 | SSW | 8 | NNE | 14 | WSW | 11 |
| 6 | WSW | 6 | WSW | 11 | NE | 8 | SSW | 5 | WSW | 6 | WSW | 18 | NE | 13 | SSW | 8 |
| 7 | NE | 7 | WSW | 8 | NNW | 4 | WNW | 11 | NE | 8 | WSW | 14 | NNW | 6 | WNW | 18 |
| 8 | S | 8 | WNW | 8 | W | 6 | N | 2 | S | 9 | WNW | 13 | W | 9 | N | 4 |
| 9 | W | 8 | NW | 9 | N | 10 | S | 2 | W | 9 | NW | 14 | N | 15 | S | 3 |
| 10 | E | 8 | N | 4 | NNW | 4 | ESE | 3 | E | 9 | N | 6 | NNW | 6 | ESE | 5 |
| 11 | E | 2 | SSW | 4 | S | 4 | S | 9 | E | 2 | SSW | 6 | S | 6 | S | 14 |
| 12 | SSW | 5 | ESE | 4 | SW | 6 | W | 20 | SSW | 6 | ESE | 6 | SW | 10 | W | 32 |
| 13 | NE | 9 | SE | 3 | ENE | 4 | W | 12 | NE | 10 | SE | 5 | ENE | 6 | W | 20 |
| 14 | NE | 10 | ESE | 3 | W | 5 | SW | 2 | NE | 12 | ESE | 5 | W | 7 | SW | 3 |
| 15 | E | 6 | ENE | 7 | NNW | 6 | WSW | 5 | E | 7 | ENE | 11 | NNW | 10 | WSW | 10 |
| 16 | SSE | 10 | ENE | 8 | WSW | 7 | WNW | 6 | SSE | 11 | ENE | 13 | WSW | 10 | WNW | 10 |
| 17 | NW | 6 | SSE | 1 | NNE | 8 | ENE | 6 | NW | 7 | SSE | 1 | NNE | 12 | ENE | 10 |
| 18 | WNW | 2 | S | 8 | N | 3 | SSE | 8 | WNW | 2 | S | 13 | N | 5 | SSE | 14 |
| 19 | SSW | 8 | SW | 2 | NW | 3 | SSW | 8 | SSW | 10 | SW | 4 | NW | 5 | SSW | 14 |
| 20 | SSW | 11 | NW | 2 | ENE | 1 | WSW | 8 | SSW | 13 | NW | 2 | ENE | 1 | WSW | 12 |
| 21 | WNW | 8 | ENE | 9 | NE | 2 | WNW | 10 | WNW | 8 | ENE | 15 | NE | 2 | WNW | 16 |
| 22 | WNW | 7 | E | 2 | ESE | 1 | WNW | 6 | WNW | 8 | E | 2 | ESE | 2 | WNW | 9 |
| 23 | NNE | 7 | NW | 16 | WSW | 2 | SSE | 4 | NNE | 8 | NW | 25 | WSW | 3 | SSE | 6 |
| 24 | ESE | 12 | NE | 9 | WSW | 1 | S | 8 | ESE | 13 | NE | 14 | WSW | 2 | S | 14 |
| 25 | SSW | 16 | S | 7 | S | 2 | SSW | 18 | SSW | 18 | S | 11 | S | 4 | SSW | 28 |
| 26 | SW | 8 | SW | 11 | SSW | 4 | WSW | 4 | SW | 8 | SW | 18 | SSW | 6 | WSW | 6 |
| 27 | ESE | 4 | WNW | 5 | SSW | 7 | WNW | 8 | ESE | 5 | WNW | 8 | SSW | 11 | WNW | 13 |
| 28 | SSW | 8 | ESE | 5 | WSW | 4 | WSW | 7 | SSW | 10 | ESE | 8 | WSW | 7 | WSW | 12 |
| 29 | NE | 5 | SW | 10 | SSW | 7 | SSW | 10 | NE | 5 | SW | 16 | SSW | 12 | SSW | 16 |
| 30 | SW | 3 | NE | 8 | WSW | 7 | W | 4 | SW | 4 | NE | 14 | WSW | 12 | W | 6 |
| 31 | | | ENE | 3 | SW | 3 | | | | | ENE | 5 | SW | 5 | | |
| Monthly Vector Resultant | SSW | 56 | WSW | 26 | WNW | 33 | SW | 142 | SSW (200°) | 65 | WSW (245°) | 39 | W (274°) | 53 | WSW (237°) | 230 |
| Daily Vector Mean | SSW | 1.9 | WSW | 0.7 | WNW | 1.1 | SW | 4.7 | SSW | 2.2 | WSW | 1.3 | W | 1.7 | WSW | 7.7 |

TABLE 11

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1954

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SW | 16 | W | 11 | WSW | 5 | WSW | 4 | SW | 18 | W | 18 | WSW | 8 | WSW | 7 |
| 2 | WSW | 12 | SSE | 3 | SSW | 5 | SSW | 12 | WSW | 14 | SSE | 5 | SSW | 8 | SSW | 20 |
| 3 | ESE | 7 | ENE | 11 | WSW | 12 | WNW | 8 | ESE | 8 | ENE | 18 | WSW | 19 | WNW | 12 |
| 4 | W | 9 | NNE | 2 | WSW | 6 | SE | 5 | W | 10 | NNE | 3 | WSW | 10 | SE | 8 |
| 5 | W | 13 | NNW | 12 | WNW | 8 | SW | 11 | W | 15 | NNW | 19 | WNW | 12 | SW | 17 |
| 6 | W | 7 | SW | 6 | NNW | 4 | ESE | 3 | W | 8 | SW | 10 | NNW | 6 | ESE | 5 |
| 7 | SSE | 4 | NNE | 2 | NE | 4 | SW | 11 | SSE | 4 | NNE | 4 | NE | 6 | SW | 18 |
| 8 | SW | 7 | NNW | 3 | S | 3 | N | 7 | SW | 8 | NNW | 5 | S | 5 | N | 11 |
| 9 | WSW | 5 | E | 4 | W | 4 | ENE | 7 | WSW | 6 | E | 6 | W | 7 | ENE | 11 |
| 10 | WSW | 6 | E | 7 | W | 10 | W | 8 | WSW | 7 | E | 11 | W | 15 | W | 12 |
| 11 | ENE | 6 | NE | 3 | WNW | 18 | N | 10 | ENE | 7 | NE | 5 | WNW | 27 | N | 16 |
| 12 | SW | 6 | SSW | 10 | NW | 9 | SSW | 2 | SW | 7 | SSW | 17 | NW | 14 | SSW | 3 |
| 13 | E | 2 | NW | 5 | WSW | 2 | S | 2 | E | 3 | NW | 8 | WSW | 4 | S | 3 |
| 14 | S | 6 | W | 8 | S | 7 | ENE | 13 | S | 7 | W | 13 | S | 12 | ENE | 21 |
| 15 | SSW | 6 | NNW | 6 | WSW | 5 | ESE | 6 | SSW | 7 | NNW | 10 | WSW | 8 | ESE | 10 |
| 16 | SSE | 6 | ENE | 4 | ESE | 2 | WNW | 4 | SSE | 6 | ENE | 7 | ESE | 4 | WNW | 6 |
| 17 | ESE | 4 | ESE | 3 | ENE | 8 | SSE | 4 | ESE | 4 | ESE | 4 | ENE | 13 | SSE | 6 |
| 18 | ENE | 10 | SW | 6 | SSE | 7 | SSE | 7 | ENE | 11 | SW | 9 | SSE | 11 | SSE | 11 |
| 19 | ESE | 4 | NW | 7 | WSW | 11 | WSW | 14 | ESE | 4 | NW | 11 | WSW | 18 | WSW | 22 |
| 20 | S | 6 | SW | 6 | NE | 4 | WSW | 7 | S | 8 | SW | 10 | NE | 6 | WSW | 11 |
| 21 | SW | 10 | NNE | 10 | ENE | 6 | W | 16 | SW | 11 | NNE | 17 | ENE | 10 | W | 25 |
| 22 | WSW | 12 | NE | 10 | ENE | 7 | WNW | 12 | WSW | 14 | NE | 16 | ENE | 12 | WNW | 19 |
| 23 | N | 7 | NE | 3 | SW | 6 | SE | 2 | N | 8 | NE | 5 | SW | 9 | SE | 2 |
| 24 | SW | 6 | ESE | 1 | SW | 9 | SSE | 8 | SW | 6 | ESE | 1 | SW | 14 | SSE | 13 |
| 25 | SW | 12 | NNE | 3 | SW | 6 | WSW | 8 | SW | 13 | NNE | 5 | SW | 10 | WSW | 13 |
| 26 | WSW | 10 | ENE | 3 | NE | 6 | W | 10 | WSW | 11 | ENE | 5 | NE | 10 | W | 15 |
| 27 | NNW | 12 | SW | 6 | ENE | 4 | SSW | 8 | NNW | 14 | SW | 9 | ENE | 7 | SSW | 14 |
| 28 | NNE | 7 | SSW | 4 | ESE | 2 | SSW | 4 | NNE | 8 | SSW | 6 | ESE | 4 | SSW | 6 |
| 29 | W | 4 | W | 4 | W | 6 | S | 13 | W | 4 | W | 7 | W | 10 | S | 20 |
| 30 | WSW | 7 | WSW | 3 | N | 10 | SSW | 11 | WSW | 8 | WSW | 5 | N | 16 | SSW | 18 |
| 31 | | | SSW | 4 | NW | 11 | | | | | SSW | 6 | NW | 18 | | |
| Monthly Vector Resultant | SW | 110 | NW | 28 | W | 76 | SW | 104 | SW | (236°) 125 | WNW | (303°) 72 | W | (269°) 135 | SW | (225°) 165 |
| Daily Vector Mean | SW | 3.7 | NW | 0.9 | W | 2.4 | SW | 3.5 | SW | 4.2 | WNW | 2.3 | W | 4.4 | SW | 5.5 |

TABLE 12

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1955

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NW | 7 | SW | 14 | NNW | 4 | NNW | 8 | NW | 11 | SW | 16 | NNW | 6 | NNW | 12 |
| 2 | ENE | 4 | W | 5 | WSW | 5 | E | 5 | ENE | 7 | W | 6 | WSW | 8 | E | 8 |
| 3 | SE | 6 | NE | 6 | W | 4 | ENE | 6 | SE | 10 | NE | 6 | W | 7 | ENE | 7 |
| 4 | SSW | 8 | WSW | 5 | WSW | 8 | NNW | 1 | SSW | 12 | WSW | 6 | WSW | 12 | NNW | 2 |
| 5 | SSW | 8 | WNW | 4 | WSW | 8 | N | 2 | SSW | 14 | WNW | 4 | WSW | 12 | N | 3 |
| 6 | SSE | 11 | | 0 | S | 3 | W | 5 | SSE | 17 | NW | 1 | S | 5 | W | 7 |
| 7 | S | 8 | SE | 4 | WNW | 5 | N | 11 | S | 12 | SE | 4 | WNW | 7 | N | 18 |
| 8 | E | 6 | SSW | 8 | NE | 10 | E | 6 | E | 9 | SSW | 10 | NE | 15 | E | 10 |
| 9 | ENE | 2 | W | 8 | NE | 4 | SSE | 6 | ENE | 4 | W | 9 | NE | 6 | SSE | 10 |
| 10 | ENE | 7 | NNE | 8 | N | 3 | SW | 11 | ENE | 12 | NNE | 8 | N | 5 | SW | 18 |
| 11 | SSW | 6 | NE | 9 | NNE | 9 | NNW | 8 | SSW | 9 | NE | 10 | NNE | 14 | NNW | 12 |
| 12 | W | 8 | ENE | 12 | NE | 11 | W | 4 | W | 12 | ENE | 13 | NE | 17 | W | 6 |
| 13 | WNW | 14 | NE | 9 | N | 12 | E | 4 | WNW | 22 | NE | 10 | N | 18 | E | 6 |
| 14 | WNW | 10 | WSW | 9 | WSW | 10 | SW | 9 | WNW | 16 | WSW | 10 | WSW | 16 | SW | 14 |
| 15 | NNW | 6 | SW | 10 | WSW | 8 | SSE | 1 | NNW | 10 | SW | 11 | WSW | 12 | SSE | 2 |
| 16 | WNW | 6 | SW | 12 | NW | 3 | S | 4 | WNW | 9 | SW | 14 | NW | 5 | S | 7 |
| 17 | ENE | 6 | WSW | 10 | ENE | 7 | SE | 3 | ENE | 10 | WSW | 11 | ENE | 11 | SE | 5 |
| 18 | SE | 4 | NW | 6 | NNE | 8 | SW | 6 | SE | 7 | NW | 6 | NNE | 12 | SW | 10 |
| 19 | SSE | 3 | ENE | 7 | NW | 5 | W | 6 | SSE | 5 | ENE | 8 | NW | 8 | W | 10 |
| 20 | W | 2 | NW | 2 | SW | 9 | N | 6 | W | 3 | NW | 2 | SW | 14 | N | 9 |
| 21 | WNW | 11 | S | 3 | WSW | 10 | E | 8 | WNW | 17 | S | 3 | WSW | 16 | E | 14 |
| 22 | WNW | 14 | SW | 6 | W | 5 | ENE | 8 | WNW | 23 | SW | 7 | W | 8 | ENE | 14 |
| 23 | W | 8 | WSW | 7 | NNE | 11 | ENE | 2 | W | 12 | WSW | 8 | NNE | 18 | ENE | 3 |
| 24 | WNW | 7 | NE | 5 | E | 5 | NW | 7 | WNW | 11 | NE | 6 | E | 8 | NW | 12 |
| 25 | N | 10 | E | 3 | NE | 4 | N | 10 | N | 16 | E | 3 | NE | 6 | N | 16 |
| 26 | N | 7 | SW | 6 | S | 5 | ENE | 6 | N | 11 | SW | 7 | S | 8 | ENE | 10 |
| 27 | ESE | 4 | WSW | 7 | WNW | 2 | S | 9 | ESE | 6 | WSW | 8 | WNW | 3 | S | 14 |
| 28 | E | 3 | ENE | 7 | SE | 5 | WSW | 8 | E | 5 | ENE | 8 | SE | 8 | WSW | 12 |
| 29 | SW | 8 | NE | 5 | SSW | 9 | SSE | 12 | SW | 13 | NE | 6 | SSW | 14 | SSE | 18 |
| 30 | SW | 7 | S | 5 | W | 10 | WSW | 12 | SW | 11 | S | 5 | W | 17 | WSW | 19 |
| 31 | | | SSW | 6 | W | 8 | | | | | SSW | 7 | W | 12 | | |
| Monthly Vector Resultant | W | 59 | WSW | 47 | WNW | 59 | W | 12 | WNW (284°) | 86 | WSW (238°) | 56 | WNW (300°) | 90 | W (265°) | 16 |
| Daily Vector Mean | W | 2.0 | WSW | 1.5 | WNW | 2.0 | W | 0.4 | WNW | 2.8 | WSW | 1.8 | WNW | 2.9 | W | 0.5 |

TABLE 13

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1956

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNW | 8 | SSW | 13 | NNE | 7 | SW | 5 | NNW | 12 | SSW | 21 | NNE | 11 | SW | 9 |
| 2 | NNE | 6 | NNE | 3 | NE | 9 | W | 9 | NNE | 10 | NNE | 5 | NE | 14 | W | 14 |
| 3 | NNW | 4 | NE | 9 | NE | 7 | S | 8 | NNW | 6 | NE | 14 | NE | 11 | S | 12 |
| 4 | WNW | 4 | ENE | 12 | S | 10 | SSW | 7 | WNW | 7 | ENE | 18 | S | 16 | SSW | 11 |
| 5 | ENE | 5 | ENE | 8 | NNE | 2 | SE | 6 | ENE | 8 | ENE | 13 | NNE | 4 | SE | 10 |
| 6 | ESE | 4 | N | 5 | NNW | 8 | WNW | 9 | ESE | 6 | N | 9 | NNW | 13 | WNW | 15 |
| 7 | S | 5 | SSW | 9 | NNW | 5 | NW | 7 | S | 8 | SSW | 15 | NNW | 8 | NW | 12 |
| 8 | N | 3 | SSW | 13 | SW | 7 | NW | 3 | N | 4 | SSW | 20 | SW | 12 | NW | 5 |
| 9 | N | 4 | WSW | 13 | SW | 10 | ENE | 6 | N | 7 | WSW | 21 | SW | 16 | ENE | 10 |
| 10 | NW | 6 | NW | 12 | W | 9 | S | 9 | NW | 10 | NW | 18 | W | 15 | S | 15 |
| 11 | SSW | 4 | SW | 9 | SW | 7 | SW | 4 | SSW | 7 | SW | 14 | SW | 12 | SW | 6 |
| 12 | WSW | 5 | SW | 3 | SSW | 3 | SW | 4 | WSW | 8 | SW | 5 | SSW | 5 | SW | 6 |
| 13 | SW | 9 | SW | 7 | SSW | 10 | SW | 12 | SW | 14 | SW | 10 | SSW | 16 | SW | 18 |
| 14 | WSW | 8 | WNW | 9 | W | 9 | NW | 7 | WSW | 13 | WNW | 14 | W | 14 | NW | 11 |
| 15 | W | 5 | SSW | 9 | WSW | 7 | E | 11 | W | 8 | SSW | 14 | WSW | 10 | E | 18 |
| 16 | SSE | 1 | N | 6 | WSW | 9 | SW | 6 | SSE | 2 | N | 9 | WSW | 15 | SW | 9 |
| 17 | ESE | 3 | NE | 8 | S | 7 | WNW | 12 | ESE | 5 | NE | 13 | S | 10 | WNW | 19 |
| 18 | NE | 5 | NE | 6 | SSW | 6 | WSW | 5 | NE | 8 | NE | 10 | SSW | 10 | WSW | 8 |
| 19 | ENE | 10 | ESE | 7 | NNW | 10 | W | 4 | ENE | 17 | ESE | 12 | NNW | 16 | W | 7 |
| 20 | S | 9 | WSW | 2 | N | 9 | NW | 8 | S | 14 | WSW | 3 | N | 14 | NW | 13 |
| 21 | WSW | 6 | SW | 7 | WNW | 3 | S | 6 | WSW | 10 | SW | 12 | WNW | 4 | S | 10 |
| 22 | WSW | 7 | SW | 9 | SSW | 13 | SSW | 8 | WSW | 11 | SW | 14 | SSW | 20 | SSW | 12 |
| 23 | SW | 9 | SW | 9 | WSW | 7 | W | 12 | SW | 15 | SW | 14 | WSW | 12 | W | 18 |
| 24 | W | 4 | SW | 6 | NW | 7 | W | 9 | W | 6 | SW | 10 | NW | 11 | W | 15 |
| 25 | NNE | 4 | WSW | 8 | WNW | 3 | E | 5 | NNE | 6 | WSW | 13 | WNW | 5 | E | 8 |
| 26 | SE | 9 | W | 3 | SSW | 6 | E | 10 | SE | 14 | W | 6 | SSW | 9 | E | 16 |
| 27 | W | 15 | W | 5 | SW | 12 | ENE | 9 | W | 24 | W | 9 | SW | 19 | ENE | 15 |
| 28 | NW | 12 | N | 2 | WSW | 12 | ESE | 5 | NW | 20 | N | 3 | WSW | 18 | ESE | 9 |
| 29 | SSW | 5 | E | 4 | SW | 11 | SSW | 10 | SSW | 7 | E | 6 | SW | 17 | SSW | 16 |
| 30 | S | 11 | E | 2 | SSW | 7 | WNW | 6 | S | 18 | E | 3 | SSW | 11 | WNW | 9 |
| 31 | | | S | 6 | SSW | 10 | | | | | S | 10 | SSW | 16 | | |
| Monthly Vector Resultant | WSW | 54 | SW | 72 | WSW | 122 | SW | 76 | W | (272°) 82 | SW | (230°) 106 | WSW | (243°) 191 | WSW | (236°) 118 |
| Daily Vector Mean | WSW | 1.8 | SW | 2.4 | WSW | 4.0 | SW | 2.6 | W | 2.7 | SW | 3.4 | WSW | 6.2 | WSW | 3.9 |

TABLE 14

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1957

| Day of Month | Daily Mean Land Winds | | | | Daily Mean Over-Water Winds | | | |
|---|---|---|---|---|---|---|---|---|
| | June | July | August | September | June | July | August | September |
| 1 | WSW 2 | NNW 9 | ENE 4 | | WSW 3 | NNW 14 | ENE 7 | |
| 2 | ENE 8 | WSW 3 | SSE 6 | | ENE 13 | WSW 6 | SSE 10 | |
| 3 | NE 1 | SW 16 | SW 8 | | NE 2 | SW 26 | SW 12 | |
| 4 | WSW 2 | SW 14 | NNW 10 | | WSW 4 | SW 23 | NNW 16 | |
| 5 | ESE 6 | WNW 16 | N 13 | | ESE 10 | WNW 25 | N 20 | |
| 6 | WNW 5 | WSW 7 | NNW 5 | | WNW 7 | WSW 12 | NNW 8 | |
| 7 | ENE 7 | SW 6 | WSW 5 | | ENE 11 | SW 9 | WSW 7 | |
| 8 | ENE 11 | SW 15 | SW 9 | | ENE 18 | SW 23 | SW 14 | |
| 9 | ESE 9 | NNW 9 | W 9 | | ESE 15 | NNW 14 | W 14 | |
| 10 | SSE 7 | NW 7 | W 2 | No | SSE 10 | NW 10 | W 4 | No |
| 11 | SW 12 | NW 5 | NNF 2 | Record | SW 19 | NW 8 | NNE 3 | Record |
| 12 | E 2 | SW 7 | ENE 8 | Taken | E 4 | SW 10 | ENE 12 | Taken |
| 13 | S 8 | WSW 8 | ESE 3 | August 31, | S 13 | WSW 13 | ESE 4 | August 31, |
| 14 | SSW 16 | NE 2 | SW 6 | 1957, to | SSW 25 | NE 4 | SW 10 | 1957, to |
| 15 | SW 13 | ENE 12 | W 5 | April 1, | SW 21 | ENE 18 | W 8 | April 1, |
| 16 | SW 7 | ENE 8 | N 11 | 1958 | SW 11 | ENE 13 | N 17 | 1958 |
| 17 | SE 5 | ENE 7 | NE 3 | | SE 8 | ENE 12 | NE 4 | |
| 18 | SW 8 | NE 10 | ESE 3 | | SW 12 | NE 16 | ESE 5 | |
| 19 | WNW 14 | NE 4 | E 7 | | WNW 22 | NE 6 | E 11 | |
| 20 | WSW 5 | SSW 3 | NW 8 | | WSW 8 | SSW 5 | NW 13 | |
| 21 | SSW 10 | WSW 10 | NE 2 | | SSW 16 | WSW 16 | NE 4 | |
| 22 | SSW 14 | W 7 | ENE 8 | | SSW 22 | W 12 | ENE 13 | |
| 23 | SW 14 | NE 12 | WSW 6 | | SW 23 | NE 20 | WSW 10 | |
| 24 | NNW 6 | NE 9 | SSW 6 | | NNW 9 | NE 15 | SSW 9 | |
| 25 | WSW 10 | E 5 | N 9 | | WSW 16 | E 8 | N 15 | |
| 26 | SSW 13 | SE 2 | WNW 7 | | SSW 20 | SE 3 | WNW 12 | |
| 27 | SSW 3 | E 3 | NE 4 | | SSW 5 | E 6 | NE 7 | |
| 28 | SSW 7 | ENE 5 | ENE 6 | | SSW 10 | ENE 8 | ENE 9 | |
| 29 | W 17 | SSW 5 | N 3 | | W 28 | SSW 7 | N 5 | |
| 30 | WNW 13 | W 7 | E 2 | | WNW 21 | W 11 | E 4 | |
| 31 | | N 8 | E 7 | | | N 12 | E 10 | |
| Monthly Vector Resultant | SW 127 | WNW 53 | NNW 41 | | SW (220°) 201 | WNW (290°) 80 | NNW (348°) 69 | |
| Daily Vector Mean | SW 4.2 | WNW 1.7 | NNW 1.3 | | SW 6.7 | WNW 2.6 | NNW 2.2 | |

TABLE 15

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1958

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | WNW | 7 | WSW | 17 | NE | 7 | WNW | 7 | WNW | 10 | WSW | 27 | NE | 12 | WNW | 10 |
| 2 | ENE | 11 | SW | 11 | ESE | 3 | SSE | 5 | ENE | 5 | SW | 17 | ESE | 5 | SSE | 8 |
| 3 | E | 10 | S | 1 | N | 9 | SSW | 9 | E | 16 | S | 2 | N | 14 | SSW | 15 |
| 4 | SE | 7 | SSW | 4 | N | 5 | WSW | 10 | SE | 10 | SSW | 7 | N | 8 | WSW | 16 |
| 5 | NW | 8 | SW | 11 | SW | 10 | E | 9 | NW | 13 | SW | 17 | SW | 16 | E | 15 |
| 6 | N | 8 | S | 1 | SW | 12 | SW | 13 | N | 13 | S | 2 | SW | 18 | SW | 21 |
| 7 | S | 12 | WSW | 5 | SW | 10 | WNW | 12 | S | 19 | WSW | 8 | SW | 16 | WNW | 18 |
| 8 | WSW | 16 | NW | 8 | WNW | 3 | NW | 7 | WSW | 25 | NW | 12 | WNW | 6 | NW | 10 |
| 9 | SE | 10 | S | 6 | SSW | 5 | SW | 13 | SE | 16 | S | 9 | SSW | 8 | SW | 20 |
| 10 | WSW | 10 | WSW | 9 | WSW | 14 | NNW | 12 | WSW | 16 | WSW | 15 | WSW | 23 | NNW | 19 |
| 11 | W | 5 | NE | 1 | NNW | 3 | NNE | 5 | W | 8 | NE | 2 | NNW | 5 | NNE | 9 |
| 12 | SSE | 6 | NE | 3 | SW | 6 | WSW | 5 | SSE | 10 | NE | 6 | SW | 10 | WSW | 8 |
| 13 | SW | 12 | SE | 6 | E | 5 | WSW | 8 | SW | 18 | SE | 10 | E | 7 | WSW | 13 |
| 14 | N | 8 | S | 9 | SW | 5 | SSW | 11 | N | 12 | S | 15 | SW | 9 | SSW | 17 |
| 15 | NNW | 6 | WSW | 8 | WSW | 10 | SW | 14 | NNW | 10 | WSW | 13 | WSW | 16 | SW | 23 |
| 16 | WNW | 13 | WNW | 11 | NNE | 4 | NNE | 3 | WNW | 20 | WNW | 18 | NNE | 7 | NNE | 4 |
| 17 | WNW | 8 | NE | 7 | W | 7 | ESE | 3 | WNW | 13 | NE | 10 | W | 12 | ESE | 6 |
| 18 | ESE | 3 | S | 1 | NNW | 7 | NNW | 13 | ESE | 4 | S | 1 | NNW | 10 | NNW | 20 |
| 19 | SW | 12 | WNW | 10 | SW | 6 | W | 3 | SW | 18 | WNW | 16 | SW | 9 | W | 6 |
| 20 | SW | 6 | E | 12 | SW | 13 | SSE | 7 | SW | 9 | E | 18 | SW | 21 | SSE | 11 |
| 21 | NNE | 8 | ENE | 9 | WNW | 6 | WNW | 5 | NNE | 13 | ENE | 14 | WNW | 10 | WNW | 9 |
| 22 | SSW | 7 | SSW | 3 | N | 9 | NW | 3 | SSW | 10 | SSW | 6 | N | 14 | NW | 5 |
| 23 | NNE | 3 | SSW | 1 | ESE | 4 | S | 7 | NNE | 5 | SSW | 2 | ESE | 6 | S | 12 |
| 24 | SSW | 7 | SW | 3 | SW | 5 | SW | 14 | SSW | 12 | SW | 4 | SW | 8 | SW | 23 |
| 25 | SSW | 11 | WSW | 7 | WNW | 8 | SW | 17 | SSW | 17 | WSW | 12 | WNW | 12 | SW | 27 |
| 26 | W | 14 | W | 2 | SSW | 6 | NNW | 5 | W | 22 | W | 4 | SSW | 9 | NNW | 7 |
| 27 | WNW | 9 | SSE | 3 | S | 7 | NNW | 9 | WNW | 14 | SSE | 6 | S | 12 | NNW | 14 |
| 28 | WSW | 8 | WSW | 13 | SSW | 7 | NNW | 10 | WSW | 13 | WSW | 21 | SSW | 12 | NNW | 16 |
| 29 | SW | 15 | WSW | 12 | SSW | 9 | SSW | 7 | SW | 23 | WSW | 19 | SSW | 14 | SSW | 10 |
| 30 | WSW | 16 | W | 6 | SW | 15 | SW | 14 | WSW | 25 | W | 10 | SW | 24 | SW | 22 |
| 31 | | | ENE | 8 | W | 16 | | | | | ENE | 13 | W | 26 | | |
| Monthly Vector Resultant | WSW | 118 | WSW | 94 | WSW | 128 | WSW | 130 | WSW (254°) | 209 | WSW (238°) | 152 | WSW (245°) | 207 | WSW (249°) | 207 |
| Daily Vector Mean | WSW | 3.9 | WSW | 3.0 | WSW | 4.1 | WSW | 4.3 | WSW | 7.0 | WSW | 4.9 | WSW | 6.7 | WSW | 6.7 |

TABLE 16

LAKE ERIE - VECTOR WIND VELOCITIES AT TOLEDO, OHIO - 1959

| Day of Month | Daily Mean Land Winds | | | | Daily Mean Over-Water Winds | | | |
|---|---|---|---|---|---|---|---|---|
| | June | July | August | September | June | July | August | September |
| 1 | SW 2 | W 5 | N 4 | NE 6 | SW 3 | W 7 | N 6 | NE 10 |
| 2 | NNE 7 | NW 6 | ENE 5 | NW 4 | NNE 12 | NW 10 | ENE 8 | NW 7 |
| 3 | W 3 | NE 3 | SSE 3 | WSW 5 | W 5 | NE 4 | SSE 6 | WSW 8 |
| 4 | S 4 | S 3 | SSW 1 | SSW 5 | S 7 | S 4 | SSW 2 | SSW 8 |
| 5 | SW 3 | SW 7 | N 2 | ESE 4 | SW 6 | SW 11 | N 3 | ESE 6 |
| 6 | NNW 3 | NW 8 | ESE 3 | SSW 5 | NNW 6 | NW 13 | ESE 5 | SSW 9 |
| 7 | SE 2 | ESE 1 | E 6 | SSW 5 | SE 3 | ESE 2 | E 10 | SSW 9 |
| 8 | SSW 5 | S 5 | N 10 | SSW 2 | SSW 7 | S 9 | N 16 | SSW 4 |
| 9 | SSW 4 | WNW 7 | NNE 2 | SSE 3 | SSW 6 | WNW 12 | NNE 3 | SSE 5 |
| 10 | SSW 4 | WSW 5 | WNW 7 | WNW 7 | SSW 6 | WSW 7 | WNW 12 | WNW 12 |
| 11 | S 6 | WSW 5 | SSW 5 | NNE 5 | S 10 | WSW 8 | SSW 7 | NNE 8 |
| 12 | WSW 5 | WNW 5 | SW 6 | NE 5 | WSW 9 | WNW 9 | SW 9 | NE 8 |
| 13 | N 10 | WNW 1 | SW 6 | NNE 2 | N 16 | WNW 1 | SW 10 | NNE 3 |
| 14 | N 6 | ENE 4 | SSW 6 | NW 2 | N 9 | ENE 6 | SSW 10 | NW 3 |
| 15 | WNW 1 | NE 7 | SSW 7 | NNW 3 | WNW 2 | NE 12 | SSW 11 | NNW 5 |
| 16 | N 5 | E 3 | SW 7 | NNE 8 | N 8 | E 6 | SW 12 | NNE 13 |
| 17 | NE 5 | S 4 | SW 7 | N 5 | NE 7 | S 7 | SW 12 | N 8 |
| 18 | NNE 2 | SW 7 | N 3 | WSW 3 | NNE 3 | SW 12 | N 4 | WSW 5 |
| 19 | NNW 7 | N 4 | ENE 3 | ESE 3 | NNW 10 | N 6 | ENE 5 | ESE 5 |
| 20 | WNW 6 | NNE 8 | SW 4 | SSE 4 | WNW 10 | NNE 13 | SW 6 | SSE 6 |
| 21 | WNW 5 | SW 3 | WSW 8 | SW 9 | WNW 7 | SW 4 | WSW 13 | SW 15 |
| 22 | NE 3 | S 3 | W 5 | SW 5 | NE 5 | S 5 | W 8 | SW 7 |
| 23 | E 2 | SSW 8 | WSW 3 | SW 9 | E 4 | SSW 12 | WSW 4 | SW 14 |
| 24 | S 3 | W 8 | SW 1 | NE 3 | S 6 | W 13 | SW 2 | NE 5 |
| 25 | SW 5 | NE 5 | SSW 3 | E 8 | SW 8 | NE 9 | SSW 4 | E 13 |
| 26 | WSW 8 | SW 2 | SW 7 | SSE 7 | WSW 12 | SW 4 | SW 12 | SSE 11 |
| 27 | SW 10 | WNW 2 | SW 8 | SW 7 | SW 16 | WNW 3 | SW 13 | SW 11 |
| 28 | SW 12 | SSW 5 | SW 5 | SSW 10 | SW 19 | SSW 7 | SW 9 | SSW 16 |
| 29 | W 9 | SSE 3 | SSW 1 | WNW 4 | W 15 | SSE 6 | SSW 2 | WNW 6 |
| 30 | E 6 | WNW 7 | NNW 1 | NNE 7 | E 10 | WNW 10 | NNW 2 | NNE 12 |
| 31 | | N 6 | NNW 7 | | | N 10 | NNW 12 | |
| Monthly Vector Resultant | W 49 | W 47 | WSW 86 | SW 26 | W (263°) 78 | W (270°) 75 | WSW (237°) 100 | SW (223°) 41 |
| Daily Vector Mean | W 1.6 | W 1.5 | WSW 2.8 | SW 0.9 | W 2.6 | W 2.4 | WSW 3.2 | SW 1.4 |

TABLE 17

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1950

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SW | 12 | WSW | 8 | N | 7 | ENE | 4 | SW | 11 | WSW | 10 | N | 8 | ENE | 4 |
| 2 | SSW | 12 | S | 14 | SSW | 13 | NNE | 10 | SSW | 11 | S | 15 | SSW | 15 | NNE | 11 |
| 3 | SW | 10 | SW | 4 | SW | 12 | NNW | 3 | SW | 9 | SW | 4 | SW | 14 | NNW | 4 |
| 4 | WSW | 16 | SW | 6 | W | 9 | NW | 12 | WSW | 14 | SW | 7 | W | 10 | NW | 14 |
| 5 | SW | 18 | SSW | 6 | WNW | 10 | NW | 7 | SW | 16 | SSW | 7 | WNW | 11 | NW | 8 |
| 6 | SW | 19 | WSW | 10 | N | 6 | S | 4 | SW | 17 | WSW | 11 | N | 7 | S | 4 |
| 7 | SW | 10 | SW | 12 | ENE | 6 | SE | 2 | SW | 9 | SW | 14 | ENE | 7 | SE | 3 |
| 8 | SSW | 9 | SSW | 8 | SSE | 7 | E | 5 | SSW | 8 | SSW | 9 | SSE | 8 | E | 6 |
| 9 | S | 11 | ESE | 5 | SSW | 10 | SE | 5 | S | 10 | ESE | 6 | SSW | 11 | SE | 6 |
| 10 | SW | 14 | E | 8 | SSW | 12 | ENE | 9 | SW | 13 | E | 9 | SSW | 14 | ENE | 10 |
| 11 | WNW | 13 | S | 4 | NNW | 9 | NE | 13 | WNW | 12 | S | 4 | NNW | 10 | NE | 15 |
| 12 | SSW | 10 | SSW | 10 | N | 4 | NE | 15 | SSW | 9 | SSW | 12 | N | 4 | NE | 17 |
| 13 | S | 9 | SSW | 10 | SW | 7 | SSE | 10 | S | 8 | SSW | 11 | SW | 8 | SSE | 12 |
| 14 | NE | 4 | WSW | 10 | SSW | 3 | SSW | 11 | NE | 4 | WSW | 11 | SSW | 3 | SSW | 12 |
| 15 | ESE | 6 | SSE | 10 | SSE | 6 | WSW | 17 | ESE | 5 | SSE | 11 | SSE | 6 | WSW | 19 |
| 16 | SSE | 11 | SSW | 10 | S | 11 | NW | 8 | SSE | 10 | SSW | 12 | S | 12 | NW | 9 |
| 17 | WNW | 16 | SSW | 19 | SSW | 6 | W | 1 | WNW | 14 | SSW | 22 | SSW | 7 | W | 1 |
| 18 | SW | 3 | WSW | 12 | NNE | 7 | SSE | 9 | SW | 3 | WSW | 14 | NNE | 8 | SSE | 10 |
| 19 | S | 5 | W | 2 | SW | 3 | NNW | 3 | S | 5 | W | 3 | SW | 3 | NNW | 4 |
| 20 | SSW | 14 | NE | 13 | WNW | 8 | E | 5 | SSW | 13 | NE | 14 | WNW | 9 | E | 5 |
| 21 | WSW | 9 | WSW | 1 | SW | 9 | ENE | 6 | WSW | 8 | WSW | 1 | SW | 10 | ENE | 6 |
| 22 | S | 4 | S | 8 | S | 9 | SSW | 4 | S | 4 | S | 9 | S | 10 | SSW | 5 |
| 23 | SSW | 14 | SE | 10 | S | 11 | WNW | 14 | SSW | 13 | SE | 12 | S | 12 | WNW | 16 |
| 24 | SSW | 19 | SSE | 11 | SSE | 5 | W | 14 | SSW | 17 | SSE | 13 | SSE | 6 | W | 15 |
| 25 | WNW | 8 | SW | 18 | SSW | 8 | S | 10 | WNW | 7 | SW | 20 | SSW | 10 | S | 11 |
| 26 | SSW | 12 | WSW | 8 | ENE | 11 | SSW | 14 | SSW | 11 | WSW | 8 | ENE | 3 | SSW | 16 |
| 27 | W | 18 | SSW | 13 | S | 8 | SE | 9 | W | 16 | SSW | 14 | S | 9 | SE | 10 |
| 28 | SW | 14 | SSW | 8 | SSW | 12 | SSE | 7 | SW | 13 | SSW | 8 | SSW | 13 | SSE | 8 |
| 29 | SW | 8 | SSW | 13 | SSW | 12 | ESE | 4 | SW | 7 | SSW | 15 | SSW | 13 | ESE | 5 |
| 30 | SW | 10 | SW | 10 | NE | 10 | SSE | 6 | SW | 9 | SW | 11 | NE | 11 | SSE | 7 |
| 31 | | | SSW | 11 | S | 6 | | | | | SSW | 12 | S | 7 | | |
| Monthly Vector Resultant | SW | 271 | SSW | 217 | SSW | 112 | S | 24 | SW (221°) | 254 | SSW (204°) | 246 | SSW (208°) | 133 | S (177°) | 27 |
| Daily Vector Mean | SW | 9 | SSW | 7 | SSW | 3.6 | S | 0.8 | SW | 8.5 | SSW | 8.0 | SSW | 4.3 | S | 0.9 |

TABLE 18

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1951

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SSW | 10 | SSW | 13 | WNW | 10 | NE | 16 | SSW | 11 | SSW | 15 | WNW | 12 | NE | 18 |
| 2 | N | 3 | SW | 13 | SSW | 10 | NNE | 4 | N | 4 | SW | 14 | SSW | 11 | NNE | 4 |
| 3 | SSW | 6 | SE | 4 | WSW | 9 | SW | 2 | SSW | 7 | SE | 5 | WSW | 10 | SW | 3 |
| 4 | WSW | 8 | SSW | 13 | N | 12 | W | 6 | WSW | 8 | SSW | 15 | N | 13 | W | 7 |
| 5 | NNE | 8 | WNW | 12 | NNW | 4 | ESE | 5 | NNE | 10 | WNW | 14 | NNW | 5 | ESE | 5 |
| 6 | NNE | 3 | WNW | 11 | SE | 9 | SSW | 7 | NNE | 3 | WNW | 12 | SE | 10 | SSW | 8 |
| 7 | NE | 7 | SSW | 12 | SSE | 7 | WNW | 13 | NE | 8 | SSW | 13 | SSE | 8 | WNW | 15 |
| 8 | ENE | 10 | SSW | 15 | SW | 13 | SW | 10 | ENE | 12 | SSW | 17 | SW | 15 | SW | 11 |
| 9 | ESE | 10 | SSW | 20 | SSW | 12 | SSE | 3 | ESE | 11 | SSW | 22 | SSW | 14 | SSE | 3 |
| 10 | SW | 12 | SW | 14 | ENE | 7 | SSE | 15 | SW | 13 | SW | 16 | ENE | 8 | SSE | 17 |
| 11 | SW | 10 | NNE | 12 | NE | 4 | SSW | 16 | SW | 11 | NNE | 14 | NE | 4 | SSW | 18 |
| 12 | E | 8 | N | 9 | NNE | 5 | S | 8 | E | 8 | N | 10 | NNE | 6 | S | 9 |
| 13 | SE | 10 | NNW | 6 | WSW | 1 | SSW | 4 | SE | 11 | NNW | 6 | WSW | 1 | SSW | 4 |
| 14 | WNW | 9 | S | 7 | WNW | 2 | SSW | 9 | WNW | 10 | S | 8 | WNW | 3 | SSW | 10 |
| 15 | WSW | 4 | SSW | 10 | NE | 10 | SW | 12 | WSW | 5 | SSW | 11 | NE | 11 | SW | 13 |
| 16 | SSW | 9 | SW | 8 | SW | 9 | SW | 11 | SSW | 10 | SW | 10 | SW | 10 | SW | 12 |
| 17 | SE | 7 | NE | 13 | NNE | 8 | SSW | 10 | SE | 8 | NE | 14 | NNE | 9 | SSW | 11 |
| 18 | S | 7 | SE | 2 | SW | 4 | SW | 11 | S | 8 | SE | 3 | SW | 4 | SW | 12 |
| 19 | SSE | 8 | WSW | 8 | S | 5 | SSW | 12 | SSE | 8 | WSW | 9 | S | 6 | SSW | 14 |
| 20 | SSW | 16 | W | 15 | SW | 9 | S | 7 | SSW | 18 | W | 17 | SW | 10 | S | 8 |
| 21 | SW | 12 | S | 16 | SSW | 21 | SSW | 12 | SW | 13 | S | 18 | SSW | 24 | SSW | 13 |
| 22 | ESE | 9 | SSW | 16 | W | 18 | SSW | 18 | ESE | 10 | SSW | 18 | W | 20 | SSW | 20 |
| 23 | SW | 16 | WSW | 7 | NNW | 8 | W | 13 | SW | 17 | WSW | 8 | NNW | 9 | W | 14 |
| 24 | SSW | 11 | NNW | 4 | N | 3 | S | 8 | SSW | 12 | NNW | 4 | N | 3 | S | 9 |
| 25 | W | 6 | SSW | 9 | NNE | 3 | WSW | 5 | W | 7 | SSW | 10 | NNE | 4 | WSW | 5 |
| 26 | SSE | 3 | SW | 16 | ESE | 4 | E | 5 | SSE | 3 | SW | 18 | ESE | 5 | E | 5 |
| 27 | SW | 15 | SSW | 5 | SSW | 2 | SW | 22 | SW | 17 | SSW | 5 | SSW | 3 | SW | 24 |
| 28 | SW | 1 | NE | 9 | E | 6 | W | 20 | SW | 1 | NE | 10 | E | 7 | W | 22 |
| 29 | SW | 14 | NNE | 8 | SSW | 7 | W | 7 | SW | 16 | NNE | 9 | SSW | 8 | W | 8 |
| 30 | S | 6 | SSW | 10 | SSE | 2 | SSE | 8 | S | 7 | SSW | 11 | SSE | 3 | SSE | 8 |
| 31 | | | SW | 13 | S | 8 | | | | | SW | 15 | S | 8 | | |
| Monthly Vector Resultant | SSW | 134 | SW | 176 | SW | 66 | SW | 195 | SSW (198°) | 145 | SW (222°) | 200 | SW (222°) | 84 | SW (215°) | 218 |
| Daily Vector Mean | SSW | 4.5 | SW | 5.7 | SW | 2.1 | SW | 6.5 | SSW | 4.8 | SW | 6.5 | SW | 2.7 | SW | 7.3 |

TABLE 19

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1952

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NW | 8 | ESE | 10 | SSE | 7 | S | 10 | NW | 9 | ESE | 11 | SSE | 8 | S | 11 |
| 2 | WSW | 6 | SSE | 6 | SSE | 8 | SSW | 10 | WSW | 6 | SSE | 7 | SSE | 9 | SSW | 11 |
| 3 | S | 10 | SSW | 14 | SW | 1 | WSW | 12 | S | 11 | SSW | 16 | SW | 1 | WSW | 14 |
| 4 | W | 6 | SW | 11 | SSE | 17 | SW | 13 | W | 7 | SW | 13 | SSE | 19 | SW | 14 |
| 5 | SSW | 10 | WSW | 4 | SW | 11 | S | 10 | SSW | 11 | WSW | 5 | SW | 12 | S | 11 |
| 6 | SSW | 18 | E | 6 | NE | 2 | N | 2 | SSW | 21 | E | 6 | NE | 2 | N | 3 |
| 7 | WNW | 13 | SSE | 8 | NNE | 6 | NNE | 13 | WNW | 14 | SSE | 9 | NNE | 6 | NNE | 15 |
| 8 | SSW | 12 | SSE | 15 | ESE | 7 | E | 5 | SSW | 13 | SSE | 17 | ESE | 8 | E | 5 |
| 9 | SW | 18 | WSW | 5 | SE | 10 | S | 9 | SW | 20 | WSW | 5 | SE | 11 | S | 10 |
| 10 | WSW | 16 | WNW | 5 | SW | 12 | SSW | 12 | WSW | 18 | WNW | 6 | SW | 14 | SSW | 14 |
| 11 | WNW | 18 | SSW | 10 | SW | 10 | S | 10 | WNW | 20 | SSW | 11 | SW | 11 | S | 12 |
| 12 | W | 9 | SSW | 16 | NE | 2 | SSW | 7 | W | 10 | SSW | 18 | NE | 2 | SSW | 8 |
| 13 | ESE | 4 | S | 10 | WNW | 7 | S | 9 | ESE | 5 | S | 12 | WNW | 8 | S | 10 |
| 14 | SSE | 8 | SSW | 11 | S | 7 | S | 12 | SSE | 10 | SSW | 12 | S | 8 | S | 14 |
| 15 | WNW | 6 | SW | 22 | S | 12 | SW | 11 | WNW | 7 | SW | 24 | S | 13 | SW | 12 |
| 16 | ENE | 7 | SW | 4 | SW | 9 | SW | 16 | ENE | 7 | SW | 5 | SW | 10 | SW | 17 |
| 17 | SW | 18 | SSW | 9 | NW | 12 | SW | 11 | SW | 20 | SSW | 10 | NW | 13 | SW | 12 |
| 18 | SW | 18 | SSW | 14 | ENE | 7 | S | 8 | SW | 20 | SSW | 15 | ENE | 8 | S | 10 |
| 19 | W | 18 | SW | 19 | ENE | 3 | WSW | 7 | W | 20 | SW | 21 | ENE | 3 | WSW | 8 |
| 20 | NW | 8 | SSW | 12 | SSE | 6 | SW | 10 | NW | 8 | SSW | 13 | SSE | 7 | SW | 12 |
| 21 | E | 8 | SW | 16 | SSW | 7 | S | 9 | E | 10 | SW | 17 | SSW | 8 | S | 10 |
| 22 | ENE | 12 | SSW | 12 | NW | 16 | SSE | 6 | ENE | 13 | SSW | 13 | NW | 18 | SSE | 7 |
| 23 | S | 8 | SW | 14 | NW | 8 | S | 4 | S | 9 | SW | 15 | NW | 8 | S | 5 |
| 24 | SSW | 19 | WNW | 18 | SW | 5 | SSW | 10 | SSW | 21 | WNW | 19 | SW | 6 | SSW | 11 |
| 25 | SW | 17 | S | 6 | S | 12 | S | 10 | SW | 19 | S | 6 | S | 13 | S | 11 |
| 26 | SW | 17 | SSW | 14 | S | 9 | SW | 4 | SW | 19 | SSW | 15 | S | 10 | SW | 4 |
| 27 | N | 13 | W | 5 | E | 5 | S | 7 | N | 14 | W | 5 | E | 6 | S | 8 |
| 28 | N | 7 | SW | 11 | SE | 11 | S | 12 | N | 8 | SW | 12 | SE | 12 | S | 13 |
| 29 | SE | 7 | N | 9 | S | 12 | SSW | 15 | SE | 8 | N | 10 | S | 14 | SSW | 17 |
| 30 | NE | 18 | S | 12 | ENE | 7 | N | 6 | NE | 20 | S | 13 | ENE | 8 | N | 7 |
| 31 | | | NNW | 12 | SE | 14 | | | | | NNW | 14 | SE | 16 | | |
| Monthly Vector Resultant | SW | 161 | SSW | 224 | S | 112 | SSW | 237 | SW | (234°) 181 | SSW | (210°) 273 | S | (180°) 134 | SSW | (200°) 237 |
| Daily Vector Mean | SW | 5.4 | SSW | 7.2 | S | 3.6 | SSW | 7.9 | SW | 6.0 | SSW | 8.9 | S | 4.3 | SSW | 7.9 |

TABLE 20

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1953

| Day of Month | Daily Mean Land Winds June | July | August | September | Daily Mean Over-Water Winds June | July | August | September |
|---|---|---|---|---|---|---|---|---|
| 1 | N 8 | WSW 6 | NE 4 | S 10 | N 9 | WSW 6 | NE 4 | S 12 |
| 2 | SSW 12 | SW 24 | NE 14 | SSW 15 | SSW 14 | SW 27 | NE 16 | SSW 17 |
| 3 | SW 9 | SW 14 | ENE 8 | S 9 | SW 10 | SW 16 | ENE 10 | S 10 |
| 4 | SSW 9 | NNE 5 | SSW 6 | S 11 | SSW 10 | NNE 5 | SSW 7 | S 13 |
| 5 | SSW 13 | SSW 5 | N 15 | W 6 | SSW 15 | SSW 5 | N 17 | W 6 |
| 6 | SW 15 | SW 8 | NE 9 | E 6 | SW 17 | SW 9 | NE 10 | E 7 |
| 7 | NW 9 | SW 15 | SE 8 | WSW 2 | NW 10 | SW 17 | SE 9 | WSW 2 |
| 8 | SE 6 | NW 8 | SSW 8 | WNW 9 | SE 7 | NW 9 | SSW 9 | WNW 10 |
| 9 | SW 18 | WNW 13 | SW 2 | SSW 4 | SW 20 | WNW 15 | SW 2 | SSW 5 |
| 10 | W 6 | SW 11 | NW 9 | E 3 | W 7 | SW 12 | NW 11 | E 3 |
| 11 | NW 6 | SW 15 | SSW 9 | SE 10 | NW 7 | SW 17 | SSW 10 | SE 11 |
| 12 | SSE 9 | SSW 8 | SSE 8 | SSW 12 | SSE 10 | SSW 10 | SSE 8 | SSW 14 |
| 13 | N 2 | W 2 | NNE 2 | WSW 21 | N 3 | W 3 | NNE 3 | WSW 24 |
| 14 | NE 12 | S 4 | S 6 | WSW 13 | NE 13 | S 5 | S 7 | WSW 14 |
| 15 | ENE 4 | NNE 3 | W 10 | S 8 | ENE 4 | NNE 3 | W 11 | S 9 |
| 16 | SSE 12 | SW 1 | SSW 11 | W 12 | SSE 13 | SW 1 | SSW 12 | W 13 |
| 17 | SSE 12 | SSE 2 | NW 10 | NNW 9 | SSE 14 | SSE 2 | NW 11 | NNW 10 |
| 18 | SW 4 | SSW 10 | WSW 9 | SE 10 | SW 5 | SSW 11 | WSW 10 | SE 11 |
| 19 | SSW 12 | SW 7 | WNW 9 | SSE 16 | SSW 13 | SW 8 | WNW 10 | SSE 18 |
| 20 | SSW 14 | WSW 8 | NE 6 | SSW 15 | SSW 16 | WSW 9 | NE 6 | SSW 17 |
| 21 | SSW 10 | E 4 | ESE 5 | WSW 6 | SSW 11 | E 4 | ESE 5 | WSW 7 |
| 22 | SSW 13 | ESE 5 | SE 3 | WNW 12 | SSW 14 | ESE 6 | SE 4 | WNW 13 |
| 23 | WNW 12 | WNW 12 | SW 6 | NE 4 | WNW 13 | WNW 14 | SW 7 | NE 4 |
| 24 | ESE 1 | NW 14 | SSW 11 | SSE 11 | ESE 1 | NW 16 | SSW 13 | SSE 12 |
| 25 | S 11 | SSE 6 | SSW 10 | S 15 | S 12 | SSE 7 | SSW 11 | S 17 |
| 26 | SSW 18 | SSW 18 | SSW 11 | SW 14 | SSW 19 | SSW 19 | SSW 13 | SW 16 |
| 27 | SSW 3 | WSW 9 | SSW 11 | WSW 5 | SSW 3 | WSW 10 | SSW 13 | WSW 6 |
| 28 | SSW 13 | WSW 2 | SSW 11 | SW 10 | SSW 15 | WSW 3 | SSW 12 | SW 11 |
| 29 | NE 9 | SSW 14 | SSW 12 | ENE 10 | NE 10 | SSW 16 | SSW 14 | ENE 11 |
| 30 | SSW 14 | WNW 8 | SSW 13 | SW 13 | SSW 16 | WNW 9 | SSW 15 | SW 14 |
| 31 | | NW 9 | SSW 5 | | | NW 10 | SSW 6 | |
| Monthly Vector Resultant | SSW 174 | WSW 180 | SSW 93 | SSW 176 | SSW (206°) 175 | WSW (237°) 206 | SSW (210°) 106 | SSW (207°) 200 |
| Daily Vector Mean | SSW 5.8 | WSW 5.8 | SSW 3.0 | SSW 5.9 | SSW 5.2 | WSW 6.6 | SSW 3.4 | SSW 6.5 |

TABLE 21

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1954

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | S | 12 | SSW | 12 | WSW | 9 | SW | 14 | S | 13 | SSW | 13 | WSW | 10 | SW | 15 |
| 2 | SW | 25 | W | 9 | SSE | 9 | SSW | 16 | SW | 28 | W | 10 | SSE | 10 | SSW | 17 |
| 3 | E | 2 | NE | 6 | SW | 8 | WSW | 14 | E | 3 | NE | 6 | SW | 9 | WSW | 16 |
| 4 | SSW | 18 | N | 2 | WSW | 12 | S | 4 | SSW | 19 | N | 3 | WSW | 13 | S | 5 |
| 5 | SW | 21 | WNW | 8 | NW | 4 | SSW | 16 | SW | 24 | WNW | 9 | NW | 4 | SSW | 17 |
| 6 | SW | 16 | SW | 13 | NW | 14 | NE | 7 | SW | 17 | SW | 15 | NW | 16 | NE | 8 |
| 7 | SSW | 13 | NW | 8 | WSW | 9 | SSW | 18 | SSW | 14 | NW | 9 | WSW | 10 | SSW | 20 |
| 8 | NE | 3 | NW | 10 | SSW | 8 | NW | 5 | NE | 3 | NW | 11 | SSW | 9 | NW | 6 |
| 9 | E | 8 | W | 6 | ENE | 6 | NE | 10 | E | 8 | W | 7 | ENE | 7 | NE | 11 |
| 10 | SSW | 10 | ENE | 2 | SSW | 11 | S | 6 | SSW | 12 | ENE | 2 | SSW | 13 | S | 7 |
| 11 | NE | 6 | E | 4 | W | 25 | NW | 14 | NE | 6 | E | 4 | W | 28 | NW | 16 |
| 12 | SSW | 9 | S | 8 | WSW | 18 | WNW | 3 | SSW | 10 | S | 10 | WSW | 20 | WNW | 3 |
| 13 | SW | 12 | WSW | 18 | WSW | 10 | S | 11 | SW | 14 | WSW | 20 | WSW | 11 | S | 12 |
| 14 | SSW | 13 | SW | 14 | S | 10 | NE | 10 | SSW | 15 | SW | 16 | S | 11 | NE | 11 |
| 15 | ENE | 4 | NW | 15 | SW | 13 | ENE | 11 | ENE | 4 | NW | 17 | SW | 14 | ENE | 13 |
| 16 | SSE | 8 | WSW | 9 | SW | 11 | N | 4 | SSE | 9 | WSW | 10 | SW | 12 | N | 4 |
| 17 | SSE | 14 | SSE | 3 | WNW | 9 | NE | 4 | SSE | 16 | SSE | 3 | WNW | 10 | NE | 10 |
| 18 | NE | 4 | SSW | 11 | SSE | 7 | E | 2 | NE | 4 | SSW | 13 | SSE | 8 | E | 3 |
| 19 | S | 9 | WNW | 8 | SW | 16 | SSW | 15 | S | 10 | WNW | 9 | SW | 18 | SSW | 17 |
| 20 | SSW | 10 | SSW | 8 | NNW | 10 | WSW | 19 | SSW | 12 | SSW | 9 | NNW | 11 | WSW | 21 |
| 21 | SW | 15 | N | 12 | NE | 10 | S | 13 | SW | 17 | N | 13 | NE | 11 | S | 15 |
| 22 | SW | 12 | NNW | 14 | E | 9 | WSW | 22 | SW | 13 | NNW | 15 | E | 10 | WSW | 25 |
| 23 | NNW | 6 | NW | 8 | S | 10 | WSW | 15 | NNW | 6 | NW | 9 | S | 11 | WSW | 17 |
| 24 | SW | 8 | SW | 8 | SSW | 18 | ENE | 2 | SW | 8 | SW | 10 | SSW | 21 | ENE | 3 |
| 25 | SSW | 15 | SW | 2 | SW | 13 | SW | 15 | SSW | 17 | SW | 2 | SW | 15 | SW | 17 |
| 26 | SW | 14 | SSW | 12 | NE | 8 | SSW | 16 | SW | 15 | SSW | 13 | NE | 10 | SSW | 17 |
| 27 | WNW | 22 | SSW | 12 | ESE | 6 | SSW | 10 | WNW | 24 | SSW | 14 | ESE | 6 | SSW | 11 |
| 28 | NW | 18 | SSW | 8 | NNE | 5 | WSW | 8 | NW | 20 | SSW | 9 | NNE | 5 | WSW | 9 |
| 29 | NW | 6 | WSW | 1 | N | 8 | SSE | 9 | NW | 7 | WSW | 1 | N | 9 | SSE | 10 |
| 30 | S | 10 | SSW | 14 | NE | 10 | SSW | 17 | S | 11 | SSW | 16 | NE | 11 | SSW | 19 |
| 31 | | | SW | 13 | WNW | 7 | | | | | SW | 15 | WNW | 8 | | |
| Monthly Vector Resultant | SW | 220 | WSW | 156 | WSW | 146 | SW | 102 | SW (216°) | 252 | WSW (246°) | 179 | WSW (238°) | 157 | SW (216°) | 198 |
| Daily Vector Mean | SW | 7.3 | WSW | 5.0 | WSW | 4.7 | SW | 3.4 | SW | 8.4 | WSW | 5.8 | WSW | 5.1 | SW | 6.6 |

TABLE 22

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1955

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNW | 11 | SW | 16 | SW | 15 | SW | 6 | NNW | 12 | SW | 18 | SW | 17 | SW | 7 |
| 2 | N | 10 | SW | 20 | W | 5 | | 0 | N | 11 | SW | 23 | W | 6 | | 0 |
| 3 | NNE | 1 | N | 5 | SSW | 6 | E | 5 | NNE | 1 | N | 5 | SSW | 6 | E | 5 |
| 4 | SW | 10 | SW | 12 | WSW | 10 | S | 10 | SW | 11 | SW | 13 | WSW | 12 | S | 11 |
| 5 | SSW | 8 | SW | 11 | SW | 14 | W | 5 | SSW | 9 | SW | 12 | SW | 16 | W | 6 |
| 6 | ESE | 9 | NW | 4 | SSW | 10 | SSW | 10 | ESE | 10 | NW | 4 | SSW | 11 | SSW | 11 |
| 7 | SSE | 9 | NE | 8 | W | 6 | NNW | 13 | SSE | 10 | NE | 9 | W | 7 | NNW | 14 |
| 8 | ENE | 10 | SSW | 8 | NE | 16 | ENE | 4 | ENE | 11 | SSW | 8 | NE | 18 | ENE | 5 |
| 9 | ENE | 12 | SSW | 12 | SE | 10 | ESE | 8 | ENE | 13 | SSW | 13 | SE | 11 | ESE | 9 |
| 10 | SSE | 2 | NW | 10 | SE | 9 | S | 21 | SSE | 2 | NW | 11 | SE | 10 | S | 23 |
| 11 | SE | 9 | NNE | 12 | NW | 4 | NNE | 4 | SE | 10 | NNE | 13 | NW | 4 | NNE | 5 |
| 12 | SW | 11 | NE | 13 | NE | 12 | W | 7 | SW | 12 | NE | 14 | NE | 17 | W | 8 |
| 13 | W | 13 | E | 5 | NE | 23 | E | 7 | W | 15 | E | 5 | NE | 26 | E | 8 |
| 14 | WSW | 10 | S | 10 | SSE | 16 | S | 12 | WSW | 11 | S | 11 | SSE | 17 | S | 13 |
| 15 | SSW | 13 | SSW | 12 | SSW | 10 | NW | 2 | SSW | 14 | SSW | 13 | SSW | 12 | NW | 2 |
| 16 | SW | 16 | SW | 20 | SSE | 1 | ENE | 5 | SW | 18 | SW | 23 | SSE | 1 | ENE | 6 |
| 17 | SW | 13 | SW | 16 | ENE | 4 | S | 8 | SW | 15 | SW | 17 | ENE | 4 | S | 9 |
| 18 | ENE | 3 | SW | 12 | NNE | 8 | S | 10 | ENE | 3 | SW | 13 | NNE | 10 | S | 11 |
| 19 | SSW | 5 | N | 14 | SW | 6 | S | 10 | SSW | 6 | N | 15 | SW | 7 | S | 12 |
| 20 | S | 8 | E | 2 | SSW | 14 | NW | 8 | S | 9 | E | 2 | SSW | 15 | NW | 9 |
| 21 | SW | 13 | SSW | 12 | SSW | 18 | N | 6 | SW | 15 | SSW | 13 | SSW | 20 | N | 7 |
| 22 | SW | 14 | SSW | 12 | SW | 8 | ENE | 13 | SW | 16 | SSW | 13 | SW | 9 | ENE | 15 |
| 23 | WSW | 15 | SW | 20 | NNW | 12 | E | 13 | WSW | 17 | SW | 22 | NNW | 13 | E | 14 |
| 24 | SW | 13 | NNE | 10 | ENE | 4 | NW | 6 | SW | 15 | NNE | 11 | ENE | 4 | NW | 6 |
| 25 | SW | 7 | SE | 2 | SSE | 7 | NW | 9 | SW | 8 | SE | 3 | SSE | 8 | NW | 10 |
| 26 | W | 9 | SSW | 10 | SSW | 12 | NE | 6 | W | 10 | SSW | 11 | SSW | 13 | NE | 7 |
| 27 | WSW | 9 | SSW | 9 | NNE | 8 | SSE | 14 | WSW | 10 | SSW | 10 | NNE | 8 | SSE | 16 |
| 28 | SW | 9 | ENE | 12 | ENE | 11 | WSW | 13 | SW | 10 | ENE | 13 | ENE | 13 | WSW | 15 |
| 29 | SSW | 10 | ENE | 8 | SE | 4 | SSE | 9 | SSW | 12 | ENE | 9 | SE | 4 | SSE | 10 |
| 30 | SSW | 12 | SSE | 4 | SSW | 14 | SSW | 11 | SSW | 14 | SSE | 5 | SSW | 15 | SSW | 12 |
| 31 | | | SSW | 10 | WSW | 16 | | | | | SSW | 11 | WSW | 18 | | |
| Monthly Vector Resultant | SW | 170 | SW | 148 | SSW | 81 | S | 89 | SW (220°) | 193 | SW (216°) | 154 | SSW (194°) | 99 | S (173°) | 80 |
| Daily Vector Mean | SW | 5.7 | SW | 4.8 | SSW | 2.6 | S | 3.0 | SW | 6.4 | SW | 5.0 | SSW | 3.2 | S | 2.7 |

TABLE 23

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1956

| Day of | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SW | 16 | SSW | 13 | N | 5 | SSW | 7 | SW | 18 | SSW | 15 | N | 7 | SSW | 10 |
| 2 | N | 6 | SSW | 13 | ENE | 13 | SW | 14 | N | 6 | SSW | 15 | ENE | 16 | SW | 22 |
| 3 | SW | 4 | NW | 1 | E | 3 | SE | 5 | SW | 5 | NW | 1 | E | 4 | SE | 7 |
| 4 | S | 9 | NE | 16 | SSE | 6 | SSW | 9 | S | 10 | NE | 19 | SSE | 7 | SSW | 15 |
| 5 | WSW | 4 | NE | 12 | NE | 3 | SE | 8 | WSW | 5 | NE | 14 | NE | 4 | SE | 12 |
| 6 | SSE | 1 | N | 6 | NE | 9 | W | 9 | SSE | 1 | N | 7 | NE | 12 | W | 14 |
| 7 | SSW | 7 | SSW | 12 | ENE | 9 | NW | 10 | SSW | 8 | SSW | 15 | ENE | 11 | NW | 16 |
| 8 | S | 9 | SW | 6 | SSW | 12 | W | 5 | S | 10 | SW | 7 | SSW | 14 | W | 7 |
| 9 | SW | 11 | SSW | 15 | SW | 14 | N | 5 | SW | 12 | SSW | 19 | SW | 17 | N | 8 |
| 10 | WSW | 8 | WSW | 16 | SW | 16 | S | 7 | WSW | 9 | WSW | 20 | SW | 19 | S | 11 |
| 11 | SSW | 7 | SW | 18 | SW | 10 | SSW | 10 | SSW | 8 | SW | 21 | SW | 13 | SSW | 16 |
| 12 | SSW | 18 | SW | 13 | NNW | 3 | SSW | 5 | SSW | 20 | SW | 16 | NNW | 3 | SSW | 9 |
| 13 | SW | 14 | SSW | 6 | SSW | 9 | S | 12 | SW | 16 | SSW | 8 | SSW | 12 | S | 18 |
| 14 | SW | 13 | WSW | 12 | SW | 11 | W | 12 | SW | 15 | WSW | 14 | SW | 14 | W | 18 |
| 15 | SW | 8 | SW | 18 | WSW | 3 | NNE | 11 | SW | 8 | SW | 22 | WSW | 4 | NNE | 17 |
| 16 | NE | 4 | N | 3 | SSW | 12 | ENE | 9 | NE | 5 | N | 4 | SSW | 14 | ENE | 14 |
| 17 | ENE | 7 | NE | 8 | SSW | 6 | W | 7 | ENE | 8 | NE | 10 | SSW | 7 | W | 12 |
| 18 | ENE | 19 | NNE | 3 | S | 7 | W | 12 | ENE | 21 | NNE | 4 | S | 8 | W | 19 |
| 19 | E | 5 | E | 10 | WSW | 5 | S | 14 | E | 5 | E | 12 | WSW | 6 | S | 22 |
| 20 | S | 15 | SE | 11 | W | 6 | NW | 11 | S | 17 | SE | 13 | W | 8 | NW | 17 |
| 21 | SSW | 12 | SSE | 7 | NW | 8 | WSW | 14 | SSW | 13 | SSE | 9 | NW | 10 | WSW | 22 |
| 22 | SSW | 1 | SSW | 7 | S | 12 | SSE | 7 | SSW | 1 | SSW | 9 | S | 14 | SSE | 10 |
| 23 | WSW | 2 | SW | 14 | SSW | 14 | SW | 8 | WSW | 2 | SW | 18 | SSW | 18 | SW | 13 |
| 24 | SW | 8 | SW | 18 | WNW | 14 | SW | 9 | SW | 9 | SW | 21 | WNW | 16 | SW | 14 |
| 25 | W | 12 | SW | 15 | SW | 9 | NNE | 10 | W | 13 | SW | 18 | SW | 12 | NNE | 16 |
| 26 | SSE | 2 | NE | 9 | SW | 14 | ENE | 9 | SSE | 3 | NE | 11 | SW | 16 | ENE | 14 |
| 27 | SSW | 20 | SSW | 12 | SSW | 7 | NE | 11 | SSW | 23 | SSW | 14 | SSW | 9 | NE | 17 |
| 28 | W | 17 | NW | 16 | SW | 10 | ENE | 5 | W | 19 | NW | 19 | SW | 13 | ENE | 8 |
| 29 | WSW | 11 | WNW | 10 | SSW | 9 | S | 7 | WSW | 12 | WNW | 12 | SSW | 11 | S | 12 |
| 30 | S | 10 | NW | 8 | SE | 5 | SW | 11 | S | 11 | NW | 10 | SE | 6 | SW | 17 |
| 31 | | | S | 7 | S | 7 | | | | | S | 9 | S | 9 | | |
| Monthly Vector Resultant | SSW | 178 | SW | 148 | SW | 150 | SW | 91 | SSW (213°) | 202 | SW (222°) | 184 | SSW (213°) | 183 | SW (220°) | 145 |
| Daily Vector Mean | SSW | 5.9 | SW | 4.8 | SW | 4.8 | SW | 3.0 | SSW | 6.7 | SW | 5.9 | SSW | 5.9 | SW | 4.8 |

TABLE 24

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1957

| Day of Month | Daily Mean Land Winds | | | | Daily Mean Over-Water Winds | | | |
|---|---|---|---|---|---|---|---|---|
| | June | July | August | September | June | July | August | September |
| 1 | SW 8 | WNW 13 | NW 3 | S 5 | SW 10 | WNW 16 | NW 4 | S 1 |
| 2 | NNW 3 | WSW 5 | SSW 6 | S 7 | NNW 4 | WSW 7 | SSW 7 | S 9 |
| 3 | NE 1 | WSW 19 | SSW 12 | SW 18 | NE 2 | WSW 23 | SSW 14 | SW 22 |
| 4 | SW 5 | SW 13 | NW 7 | WSW 13 | SW 6 | SW 16 | NW 8 | WSW 16 |
| 5 | ESE 4 | WSW 19 | N 8 | W 12 | ESE 5 | WSW 23 | N 9 | W 15 |
| 6 | SSE 3 | WSW 12 | W 10 | SW 4 | SSE 4 | WSW 15 | W 12 | SW 5 |
| 7 | NNW 6 | SW 8 | SW 7 | S 4 | NNW 7 | SW 10 | SW 9 | S 5 |
| 8 | E 10 | SSW 11 | SSW 9 | NW 2 | E 13 | SSW 13 | SSW 12 | NW 2 |
| 9 | SE 6 | W 13 | SW 5 | E 11 | SE 8 | W 15 | SW 6 | E 13 |
| 10 | S 7 | NW 11 | NNW 3 | SE 6 | S 8 | NW 14 | NNW 4 | SE 7 |
| 11 | S 9 | WSW 7 | SSW 9 | WSW 9 | S 10 | WSW 9 | SSW 11 | WSW 11 |
| 12 | WSW 8 | SW 4 | N 10 | S 8 | WSW 10 | SW 5 | N 12 | S 9 |
| 13 | S 8 | SE 1 | NE 5 | SW 13 | S 10 | SE 1 | NE 6 | SW 15 |
| 14 | SSW 12 | WSW 9 | SSW 12 | NNW 1 | SSW 15 | WSW 10 | SSW 14 | NNW 1 |
| 15 | SW 14 | N 11 | WNW 2 | S 9 | SW 18 | N 13 | WNW 2 | S 10 |
| 16 | SSW 10 | NNE 6 | NNE 9 | WSW 12 | SSW 12 | NNE 7 | NNE 10 | WSW 14 |
| 17 | SSW 5 | ENE 6 | WSW 7 | NNE 2 | SSW 7 | ENE 8 | WSW 9 | NNE 2 |
| 18 | SSW 6 | ESE 5 | SW 2 | ENE 4 | SSW 7 | ESE 6 | SW 2 | ENE 5 |
| 19 | WSW 15 | S 4 | ESE 3 | SSE 7 | WSW 19 | S 5 | ESE 4 | SSE 8 |
| 20 | WSW 9 | SSW 8 | W 4 | SSW 10 | WSW 11 | SSW 10 | W 5 | SSW 13 |
| 21 | SSW 7 | SSW 9 | NE 7 | S 9 | SSW 9 | SSW 12 | NE 9 | S 10 |
| 22 | S 7 | WSW 8 | ENE 6 | SW 6 | S 9 | WSW 9 | ENE 8 | SW 7 |
| 23 | SW 16 | N 10 | S 7 | SW 9 | SW 19 | N 12 | S 8 | SW 10 |
| 24 | SE 1 | NNE 8 | SSW 7 | W 9 | SE 1 | NNE 10 | SSW 8 | W 11 |
| 25 | SW 13 | SW 3 | SE 3 | SW 12 | SW 16 | SW 4 | SE 4 | SW 15 |
| 26 | SSW 7 | SE 5 | WSW 7 | NNW 8 | SSW 8 | SE 7 | WSW 8 | NNW 9 |
| 27 | SSW 7 | S 3 | WNW 6 | NW 5 | SSW 9 | S 4 | WNW 7 | NW 6 |
| 28 | S 9 | SSW 6 | E 7 | 0 | S 11 | SSW 7 | E 8 | 0 |
| 29 | WSW 33 | SW 15 | ESE 3 | E 4 | WSW 41 | SW 18 | ESE 4 | E 5 |
| 30 | WSW 16 | SW 11 | W 3 | S 7 | WSW 20 | SW 13 | W 4 | S 9 |
| 31 | | WSW 5 | WNW 4 | | | WSW 6 | WNW 5 | |
| Monthly Vector Resultant | SW 201 | WSW 158 | WSW 52 | SW 136 | SW (216°) 245 | WSW (244°) 182 | WSW (241°) 66 | SW (217°) 162 |
| Daily Vector Mean | SW 6.7 | WSW 5.1 | WSW 1.7 | SW 4.5 | SW 8.2 | WSW 5.9 | WSW 2.1 | SW 5.4 |

TABLE 25

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1958

| Day of Month | Daily Mean Land Winds | | | | Daily Mean Over-Water Winds | | | |
|---|---|---|---|---|---|---|---|---|
| | June | July | August | September | June | July | August | September |
| 1 | SW 12 | SW 4 | ENE 4 | WNW 12 | SW 15 | SW 20 | ENE 5 | WNW 15 |
| 2 | NNE 14 | WSW 17 | SSW 5 | N 6 | NNE 17 | WSW 21 | SSW 6 | N 7 |
| 3 | ENE 9 | WSW 4 | S 7 | SSE 8 | ENE 12 | WSW 5 | S 8 | SSE 10 |
| 4 | ENE 3 | ENE 7 | N 10 | SW 13 | ENE 3 | ENE 9 | N 13 | SW 16 |
| 5 | SW 9 | SE 2 | SSW 7 | ENE 9 | SW 11 | SE 3 | SSW 8 | ENE 11 |
| 6 | N 7 | WSW 4 | SW 10 | S 10 | N 8 | WSW 5 | SW 13 | S 12 |
| 7 | SSW 5 | SSE 3 | SW 8 | WSW 9 | SSW 7 | SSE 4 | SW 10 | WSW 12 |
| 8 | SW 12 | WSW 8 | NW 5 | NW 12 | SW 15 | WSW 10 | NW 6 | NW 15 |
| 9 | NE 5 | SW 7 | WSW 10 | SSW 12 | NE 6 | SW 8 | WSW 13 | SSW 15 |
| 10 | S 5 | S 13 | SW 11 | WNW 17 | S 6 | S 16 | SW 13 | WNW 20 |
| 11 | SW 12 | W 4 | NNE 5 | W 7 | SW 14 | W 5 | NNE 6 | W 8 |
| 12 | SW 4 | SSW 4 | SSW 8 | SW 6 | SW 5 | SSW 5 | SSW 10 | SW 8 |
| 13 | SW 10 | SSE 1 | NW 4 | SW 10 | SW 13 | SSE 2 | NW 5 | SW 12 |
| 14 | S 12 | S 9 | SW 6 | SSW 11 | W 15 | S 12 | SW 8 | SSW 13 |
| 15 | W 8 | SSW 14 | WSW 8 | SW 15 | W 9 | SSW 18 | WSW 10 | SW 18 |
| 16 | W 16 | WSW 12 | WNW 3 | ENE 2 | W 19 | WSW 15 | WNW 4 | ENE 2 |
| 17 | WSW 12 | NNW 4 | WSW 9 | E 9 | WSW 15 | NNW 5 | WSW 10 | E 12 |
| 18 | E 1 | S 7 | NW 11 | N 11 | E 2 | S 9 | NW 13 | N 13 |
| 19 | S 4 | WNW 16 | WSW 10 | N 3 | S 5 | WNW 19 | WSW 12 | N 4 |
| 20 | S 7 | NW 9 | SSW 10 | ENE 2 | S 9 | NW 11 | SSW 13 | ENE 2 |
| 21 | WNW 7 | SE 4 | SW 11 | E 1 | WNW 9 | SE 5 | SW 14 | E 1 |
| 22 | W 4 | SSE 3 | W 7 | W 10 | W 5 | SSE 4 | W 9 | W 13 |
| 23 | SSE 5 | WSW 2 | WNW 1 | S 9 | SSE 7 | WSW 3 | WNW 1 | S 10 |
| 24 | SE 6 | SSW 5 | SSE 8 | S 9 | SE 7 | SSW 6 | SSE 10 | S 12 |
| 25 | S 12 | SW 5 | WSW 12 | SSW 18 | S 14 | SW 6 | WSW 14 | SSW 21 |
| 26 | SW 19 | WSW 1 | W 4 | NNW 9 | SW 23 | WSW 2 | W 5 | NNW 10 |
| 27 | WSW 17 | ESE 3 | SE 3 | S 3 | WSW 20 | ESE 4 | SE 3 | S 4 |
| 28 | SW 7 | SW 10 | S 6 | NW 7 | SW 8 | SW 13 | S 7 | NW 9 |
| 29 | SSW 9 | SW 14 | S 8 | S 8 | SSW 11 | SW 17 | S 9 | S 10 |
| 30 | SSW 18 | SW 15 | SSW 12 | SSW 17 | SSW 22 | SW 19 | SSW 14 | SSW 21 |
| 31 | | ESE 2 | SSW 14 | | | ESE 2 | SSW 16 | |
| Monthly Vector Resultant | SW 161 | SW 160 | SW 157 | SW 126 | SW (228°) 195 | SW (226°) 186 | SW (230°) 188 | SW (232°) 152 |
| Daily Vector Mean | SW 5.4 | SW 5.2 | SW 5.1 | SW 4.2 | SW 6.5 | SW 6.0 | SW 6.1 | SW 5.1 |

TABLE 26

LAKE ERIE - VECTOR WIND VELOCITIES AT BUFFALO, NEW YORK - 1959

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SSW | 6 | S | 8 | NNW | 8 | NW | 1 | SSW | 7 | S | 10 | NNW | 10 | NW | 1 |
| 2 | ENE | 9 | W | 16 | NE | 5 | SW | 8 | ENE | 11 | W | 19 | NE | 6 | SW | 9 |
| 3 | W | 7 | W | 5 | SSW | 6 | SW | 9 | W | 8 | W | 6 | SSW | 7 | SW | 11 |
| 4 | SW | 10 | SW | 7 | S | 8 | SSW | 9 | SW | 13 | SW | 9 | S | 10 | SSW | 10 |
| 5 | SSW | 7 | SSW | 13 | NE | 10 | SSW | 5 | SSW | 9 | SSW | 16 | NE | 12 | SSW | 6 |
| 6 | WNW | 7 | SSW | 6 | E | 9 | SSE | 5 | WNW | 8 | SSW | 7 | E | 11 | SSE | 6 |
| 7 | WSW | 5 | NW | 7 | ESE | 4 | SSW | 10 | WSW | 6 | NW | 9 | ESE | 5 | SSW | 12 |
| 8 | SSW | 9 | S | 9 | E | 9 | SSW | 10 | SSW | 11 | S | 11 | E | 10 | SSW | 13 |
| 9 | WSW | 13 | WSW | 12 | SSE | 2 | SSW | 4 | WSW | 16 | WSW | 15 | SSE | 2 | SSW | 5 |
| 10 | SSW | 10 | WSW | 10 | W | 11 | W | 5 | SSW | 12 | WSW | 12 | W | 13 | W | 6 |
| 11 | SSW | 7 | SW | 9 | W | 11 | NW | 9 | SSW | 8 | SW | 12 | W | 13 | NW | 10 |
| 12 | SSW | 11 | WSW | 7 | SW | 12 | W | 2 | SSW | 14 | WSW | 9 | SW | 14 | W | 2 |
| 13 | NNW | 7 | SE | 2 | WSW | 14 | NNE | 3 | NNW | 8 | SE | 3 | WSW | 18 | NNE | 4 |
| 14 | NNW | 18 | E | 7 | SW | 11 | SW | 3 | NNW | 22 | E | 8 | SW | 13 | SW | 4 |
| 15 | NNW | 18 | ENE | 5 | SW | 10 | NE | 8 | NNW | 22 | ENE | 6 | SW | 12 | NE | 10 |
| 16 | NNE | 12 | SSE | 5 | SW | 10 | N | 3 | NNE | 14 | SSE | 6 | SW | 13 | N | 4 |
| 17 | NE | 12 | SW | 6 | SSW | 17 | WSW | 5 | NE | 14 | SW | 7 | SSW | 21 | WSW | 6 |
| 18 | NNE | 9 | SSW | 12 | NW | 3 | WNW | 8 | NNE | 11 | SSW | 14 | NW | 4 | WNW | 10 |
| 19 | NW | 6 | W | 7 | WSW | 2 | SE | 2 | NW | 7 | W | 8 | WSW | 3 | SE | 2 |
| 20 | W | 12 | E | 6 | WSW | 8 | S | 6 | W | 14 | E | 7 | WSW | 10 | S | 8 |
| 21 | SW | 7 | WSW | 4 | SW | 13 | SSW | 12 | SW | 9 | WSW | 5 | SW | 16 | SSW | 15 |
| 22 | N | 4 | SW | 5 | ENE | 5 | SW | 10 | N | 5 | SW | 6 | ENE | 6 | SW | 12 |
| 23 | SW | 5 | SSW | 9 | ESE | 5 | SW | 11 | SW | 7 | SSW | 12 | ESE | 6 | SW | 13 |
| 24 | SW | 2 | SW | 14 | WSW | 10 | W | 6 | SW | 2 | SW | 17 | WSW | 13 | W | 7 |
| 25 | S | 3 | NW | 8 | SW | 6 | ENE | 6 | S | 3 | NW | 10 | SW | 8 | ENE | 7 |
| 26 | WSW | 10 | SW | 9 | SSW | 9 | S | 7 | WSW | 12 | SW | 11 | SSW | 11 | S | 9 |
| 27 | WSW | 11 | SW | 8 | SSW | 9 | SSW | 13 | WSW | 13 | SW | 10 | SSW | 10 | SSW | 16 |
| 28 | WSW | 14 | SW | 6 | SSW | 7 | SSW | 15 | WSW | 18 | SW | 7 | SSW | 9 | SSW | 18 |
| 29 | WSW | 12 | SW | 7 | S | 2 | SW | 6 | WSW | 14 | SW | 8 | S | 2 | SW | 7 |
| 30 | NNE | 6 | SW | 8 | ESE | 3 | NE | 7 | NNE | 8 | SW | 10 | ESE | 4 | NE | 9 |
| 31 | | | W | 11 | SSW | 6 | | | | | W | 13 | SSW | 8 | | |
| Monthly Vector Resultant | W | 114 | SW | 172 | SW | 132 | SW | 135 | W | (268°) 139 | SW | (228°) 214 | SW | (218°) 158 | SW | (216°) 147 |
| Daily Vector Mean | W | 3.8 | SW | 5.6 | SW | 4.2 | SW | 4.5 | W | 4.6 | SW | 6.9 | SW | 5.1 | SW | 4.9 |

TABLE 27

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1948

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NW | 6 | WNW | 7 | WNW | 10 | SE | 4 | NW | 10 | WNW | 12 | WNW | 18 | SE | 12 |
| 2 | NE | 3 | WSW | 6 | W | 6 | SSE | 4 | NE | 5 | WSW | 9 | W | 12 | SSE | 6 |
| 3 | SSE | 3 | S | 1 | WNW | 3 | ESE | 3 | SSE | 5 | S | 1 | WNW | 6 | ESE | 6 |
| 4 | WSW | 2 | SSE | 2 | NW | 2 | E | 1 | WSW | 2 | SSE | 4 | NW | 5 | E | 2 |
| 5 | NNE | 12 | W | 6 | NE | 9 | E | 8 | NNE | 20 | W | 10 | NE | 18 | E | 14 |
| 6 | W | 4 | NNW | 11 | N | 11 | SE | 6 | W | 6 | NNW | 18 | N | 22 | SE | 12 |
| 7 | ESE | 9 | NNE | 3 | NW | 6 | SSE | 7 | ESE | 15 | NNE | 5 | NW | 12 | SSE | 13 |
| 8 | ESE | 7 | WSW | 6 | WNW | 5 | NW | 3 | ESE | 12 | WSW | 9 | WNW | 9 | NW | 6 |
| 9 | W | 2 | W | 4 | WNW | 3 | NNE | 9 | W | 3 | W | 6 | WNW | 6 | NNE | 17 |
| 10 | SE | 2 | SW | 7 | ENE | 2 | NNW | 4 | SE | 3 | SW | 11 | ENE | 4 | NNW | 8 |
| 11 | NW | 10 | WNW | 5 | SSW | 6 | W | 3 | NW | 15 | WNW | 8 | SSW | 12 | W | 6 |
| 12 | W | 6 | E | 1 | W | 7 | WSW | 7 | W | 10 | E | 1 | W | 12 | WSW | 12 |
| 13 | NW | 9 | ESE | 2 | NW | 8 | NW | 9 | NW | 14 | ESE | 4 | NW | 16 | NW | 18 |
| 14 | W | 4 | E | 7 | N | 12 | NE | 7 | W | 7 | E | 10 | N | 23 | NE | 14 |
| 15 | NW | 4 | SE | 3 | NW | 2 | ESE | 9 | NW | 6 | SE | 4 | NW | 5 | ESE | 18 |
| 16 | NNW | 3 | ESE | 7 | ESE | 3 | ESE | 13 | NNW | 4 | ESE | 12 | ESE | 6 | ESE | 24 |
| 17 | NNW | 7 | W | 5 | NE | 2 | SW | 5 | NNW | 11 | W | 8 | NE | 4 | SW | 10 |
| 18 | WSW | 2 | WNW | 9 | SSW | 7 | WNW | 9 | WSW | 4 | WNW | 14 | SSW | 14 | WNW | 18 |
| 19 | ENE | 3 | W | 4 | NNW | 2 | E | 4 | ENE | 5 | W | 7 | NNW | 4 | E | 8 |
| 20 | W | 6 | W | 5 | NNE | 2 | NNW | 9 | W | 7 | W | 8 | NNE | 4 | NNW | 17 |
| 21 | E | 3 | W | 2 | SE | 3 | NNE | 4 | W | 4 | W | 4 | SE | 5 | NNE | 8 |
| 22 | ESE | 11 | ESE | 10 | E | 3 | NE | 8 | ESE | 18 | ESE | 16 | E | 5 | NE | 15 |
| 23 | SSW | 5 | NW | 6 | S | 3 | NE | 7 | SSW | 8 | NW | 10 | S | 6 | NE | 13 |
| 24 | W | 12 | NW | 16 | SSW | 8 | ENE | 5 | W | 20 | NW | 26 | SSW | 16 | ENE | 10 |
| 25 | N | 4 | W | 8 | W | 10 | ENE | 5 | N | 7 | W | 12 | W | 18 | ENE | 10 |
| 26 | SE | 2 | WSW | 12 | WNW | 4 | NW | 1 | SE | 3 | WSW | 18 | WNW | 8 | NW | 2 |
| 27 | E | 8 | W | 6 | WNW | 2 | NW | 3 | E | 12 | W | 10 | WNW | 4 | NW | 6 |
| 28 | SSE | 5 | W | 6 | NW | 4 | E | 1 | SSE | 7 | W | 9 | NW | 8 | E | 2 |
| 29 | SW | 13 | SW | 5 | NNW | 6 | E | 6 | SW | 20 | SW | 7 | NNW | 12 | E | 12 |
| 30 | WSW | 9 | W | 6 | NE | 4 | S | 3 | WSW | 15 | W | 10 | NE | 8 | S | 6 |
| 31 | | | NW | 13 | NE | 12 | | | | | NW | 21 | NE | 23 | | |
| Monthly Vector | WNW | | W | | NW | | ENE | | WNW | (285°) | W | (280°) | NW | (319°) | ENE | (65°) |
| Resultant | | 33 | | 104 | | 66 | | 50 | | 56 | | 160 | | 137 | | 100 |
| Daily Vector | WNW | | W | | NW | | ENE | | WNW | | W | | NW | | ENE | |
| Mean | | 1.1 | | 3.3 | | 2.1 | | 1.6 | | 1.9 | | 5.2 | | 4.4 | | 3.3 |

TABLE 28

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1949

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | ESE | 4 | NE | 6 | ESE | 4 | WSW | 18 | ESE | 6 | NE | 10 | ESE | 7 | WSW | 34 |
| 2 | SE | 5 | SW | 6 | ESE | 3 | SSW | 9 | SE | 8 | SW | 10 | ESE | 5 | SSW | 17 |
| 3 | WSW | 7 | S | 3 | NNE | 4 | SE | 4 | WSW | 11 | S | 4 | NNE | 7 | SE | 9 |
| 4 | WSW | 8 | SW | 4 | WSW | 3 | SSW | 8 | WSW | 12 | SW | 7 | WSW | 5 | SSW | 14 |
| 5 | NNW | 10 | NNE | 7 | W | 5 | SW | 8 | NNW | 15 | NNE | 11 | W | 10 | SW | 15 |
| 6 | NW | 12 | NE | 9 | SW | 6 | WNW | 3 | NW | 19 | NE | 14 | SW | 11 | WNW | 5 |
| 7 | NW | 16 | NE | 10 | SW | 5 | NE | 7 | NW | 25 | NE | 17 | SW | 10 | NE | 13 |
| 8 | SW | 2 | NE | 10 | SW | 9 | NNE | 4 | SW | 3 | NE | 16 | SW | 18 | NNE | 7 |
| 9 | NE | 5 | NE | 7 | WSW | 9 | NW | 8 | NE | 8 | NE | 12 | WSW | 17 | NW | 16 |
| 10 | ESE | 1 | NW | 6 | W | 7 | ENE | 3 | ESE | 1 | NW | 10 | W | 14 | ENE | 5 |
| 11 | SSW | 4 | ENE | 1 | WSW | 8 | NE | 8 | SSW | 7 | ENE | 2 | WSW | 15 | NE | 16 |
| 12 | SSW | 12 | NNE | 4 | SSW | 1 | E | 5 | SSW | 18 | NNE | 6 | SSW | 2 | E | 10 |
| 13 | S | 8 | WNW | 7 | ENE | 5 | ESE | 10 | S | 14 | WNW | 11 | ENE | 10 | ESE | 18 |
| 14 | S | 12 | NE | 4 | ENE | 7 | W | 9 | S | 18 | NE | 7 | ENE | 13 | W | 16 |
| 15 | S | 9 | ENE | 4 | E | 10 | SW | 6 | S | 15 | ENE | 7 | E | 18 | SW | 12 |
| 16 | E | 6 | NE | 2 | NE | 10 | SW | 10 | E | 10 | NE | 4 | NE | 20 | SW | 19 |
| 17 | NE | 11 | NE | 7 | S | 6 | SW | 9 | NE | 18 | NE | 11 | S | 10 | SW | 18 |
| 18 | E | 8 | E | 1 | NNW | 8 | SW | 10 | E | 14 | E | 2 | NNW | 15 | SW | 18 |
| 19 | ESE | 3 | SW | 8 | N | 13 | WSW | 14 | ESE | 5 | SW | 12 | N | 24 | WSW | 26 |
| 20 | ESE | 2 | WNW | 4 | NW | 11 | WNW | 10 | ESE | 4 | WNW | 6 | NW | 21 | WNW | 20 |
| 21 | SW | 10 | ENE | 6 | SW | 2 | SSW | 6 | SW | 16 | ENE | 10 | SW | 4 | SSW | 12 |
| 22 | NW | 12 | W | 9 | SW | 2 | SW | 4 | NW | 20 | W | 15 | SW | 4 | SW | 8 |
| 23 | SW | 5 | WNW | 6 | SW | 8 | NW | 8 | SW | 8 | WNW | 10 | SW | 14 | NW | 15 |
| 24 | SSW | 8 | SSW | 4 | ENE | 5 | NW | 9 | SSW | 12 | SSW | 6 | ENE | 9 | NW | 18 |
| 25 | SSE | 4 | SW | 6 | S | 6 | ENE | 2 | SSE | 6 | SW | 9 | S | 10 | ENE | 3 |
| 26 | SSW | 12 | SW | 1 | SW | 12 | ENE | 4 | SSW | 19 | SW | 2 | SW | 22 | ENE | 7 |
| 27 | NW | 4 | SW | 10 | SW | 8 | S | 13 | NW | 7 | SW | 17 | SW | 15 | S | 24 |
| 28 | NE | 10 | WSW | 8 | SW | 5 | SE | 4 | NE | 16 | WSW | 12 | SW | 10 | SE | 7 |
| 29 | ENE | 5 | WSW | 12 | N | 8 | NNW | 8 | ENE | 7 | WSW | 18 | N | 14 | NNW | 16 |
| 30 | NE | 8 | WNW | 8 | SW | 7 | WSW | 8 | NE | 14 | WNW | 12 | SW | 14 | WSW | 14 |
| 31 | | | NW | 8 | S | 12 | | | | | NW | 12 | S | 22 | | |
| Monthly Vector | SW | | NW | | WSW | | WSW | | SW | (214°) | NW | (319°) | WSW | (242°) | ENE | (62°) |
| Resultant | | 42 | | 46 | | 51 | | 92 | | 44 | | 74 | | 104 | | 175 |
| Daily Vector | SW | | NW | | WSW | | WSW | | SW | | NW | | WSW | | ENE | |
| Mean | | 1.4 | | 1.5 | | 1.6 | | 3.1 | | 1.5 | | 2.3 | | 3.3 | | 5.8 |

TABLE 29

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1950

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | SSW | 8 | SSW | 7 | NE | 11 | WNW | 5 | SSW | 14 | SSW | 10 | NE | 20 | WNW | 9 |
| 2 | SSW | 10 | E | 3 | W | 5 | NE | 4 | SSW | 17 | E | 4 | W | 10 | NE | 7 |
| 3 | NW | 6 | SSW | 3 | WSW | 10 | N | 5 | NW | 10 | SSW | 5 | WSW | 18 | N | 10 |
| 4 | WNW | 13 | SE | 2 | WSW | 9 | NW | 13 | WNW | 21 | SE | 4 | WSW | 17 | NW | 25 |
| 5 | W | 3 | ENE | 4 | WNW | 11 | NNW | 5 | W | 5 | ENE | 6 | WNW | 20 | NNW | 10 |
| 6 | WSW | 12 | WNW | 8 | NW | 3 | SSW | 3 | WSW | 19 | WNW | 13 | NW | 6 | SSW | 6 |
| 7 | SSW | 10 | SW | 5 | ESE | 3 | WSW | 2 | SSW | 15 | SW | 8 | ESE | 6 | WSW | 4 |
| 8 | S | 9 | SW | 4 | S | 6 | NNE | 6 | S | 15 | SW | 6 | S | 10 | NNE | 12 |
| 9 | SSW | 8 | ENE | 2 | WSW | 7 | NE | 7 | SSW | 12 | ENE | 4 | WSW | 13 | NE | 13 |
| 10 | SW | 10 | NNE | 4 | WSW | 7 | NE | 13 | SW | 16 | NNE | 6 | WSW | 14 | NE | 25 |
| 11 | NW | 10 | NE | 6 | NW | 6 | ENE | 16 | NW | 16 | NE | 9 | NW | 10 | ENE | 30 |
| 12 | SSW | 2 | SSW | 4 | WNW | 2 | NE | 20 | SSW | 4 | SSW | 6 | WNW | 5 | NE | 38 |
| 13 | S | 6 | WSW | 7 | NNW | 4 | ENE | 15 | S | 9 | WSW | 10 | NNW | 7 | ENE | 28 |
| 14 | NE | 6 | SSW | 12 | SSW | 3 | SW | 9 | NE | 10 | SSW | 18 | SSW | 6 | SW | 17 |
| 15 | ENE | 8 | NE | 6 | ENE | 5 | W | 11 | ENE | 12 | NE | 10 | ENE | 9 | W | 20 |
| 16 | NE | 4 | SSW | 4 | SW | 2 | NNW | 8 | NE | 7 | SSW | 7 | SW | 4 | NNW | 16 |
| 17 | NW | 18 | SW | 10 | | 0 | W | 5 | NW | 28 | SW | 15 | E | 1 | W | 10 |
| 18 | SW | 2 | WNW | 11 | N | 6 | SSW | 8 | SW | 4 | WNW | 18 | N | 12 | SSW | 15 |
| 19 | SE | 4 | WNW | 3 | NNW | 3 | NW | 6 | SE | 6 | WNW | 5 | NNW | 6 | NW | 6 |
| 20 | S | 6 | NE | 8 | NW | 11 | ENE | 6 | S | 10 | NE | 12 | NW | 20 | ENE | 12 |
| 21 | WNW | 8 | SSW | 3 | SW | 8 | ENE | 6 | WNW | 12 | SSW | 4 | SW | 14 | ENE | 10 |
| 22 | NE | 7 | SSW | 6 | SW | 5 | SW | 3 | NE | 10 | SSW | 10 | SW | 10 | SW | 6 |
| 23 | E | 3 | ENE | 4 | SSW | 10 | WNW | 12 | E | 5 | ENE | 7 | SSW | 18 | WNW | 23 |
| 24 | WNW | 8 | SSW | 6 | SE | 2 | WNW | 12 | WNW | 12 | SSW | 9 | SE | 4 | WNW | 24 |
| 25 | NW | 7 | WNW | 8 | SW | 3 | WSW | 6 | NW | 11 | WNW | 14 | SW | 5 | WSW | 12 |
| 26 | W | 6 | SSW | 4 | NE | 7 | SSE | 5 | W | 9 | SSW | 6 | NE | 13 | SSE | 9 |
| 27 | WNW | 12 | WSW | 6 | SW | 2 | E | 4 | WNW | 18 | WSW | 10 | SW | 4 | E | 7 |
| 28 | SSW | 12 | W | 5 | SSW | 4 | ENE | 4 | SSW | 18 | W | 8 | SSW | 7 | ENE | 7 |
| 29 | SSW | 8 | WSW | 5 | ENE | 6 | E | 5 | SSW | 12 | WSW | 8 | ENE | 12 | E | 10 |
| 30 | SSW | 10 | SW | 2 | ENE | 13 | E | 4 | SSW | 15 | SW | 3 | ENE | 24 | E | 8 |
| 31 | | | NE | 4 | E | 2 | | | | | NE | 7 | E | 4 | | |
| Monthly Vector | WSW | | WSW | | W | | N | | WSW | (247°) | WSW | (239°) | W | (273°) | N | (8°) |
| Resultant | | 105 | | 55 | | 46 | | 70 | | 177 | | 93 | | 81 | | 131 |
| Daily Vector | WSW | | WSW | | W | | N | | WSW | | WSW | | W | | N | |
| Mean | | 3.5 | | 1.8 | | 1.5 | | 2.4 | | 5.9 | | 3.0 | | 2.6 | | 4.4 |

TABLE 30

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1951

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNE | 1 | SW | 4 | NW | 11 | NE | 14 | NNE | 2 | SW | 7 | NW | 21 | NE | 27 |
| 2 | ESE | 5 | WSW | 8 | S | 5 | NNE | 6 | ESE | 8 | WSW | 13 | S | 9 | NNE | 10 |
| 3 | E | 5 | NE | 2 | WNW | 10 | WNW | 5 | E | 8 | NE | 4 | WNW | 18 | WNW | 9 |
| 4 | NW | 9 | ESE | 7 | NNW | 9 | WNW | 3 | NW | 15 | ESE | 10 | NNW | 17 | WNW | 6 |
| 5 | NE | 2 | NW | 14 | ESE | 1 | E | 3 | NE | 4 | NW | 23 | ESE | 1 | E | 6 |
| 6 | SW | 5 | NW | 11 | NE | 8 | WSW | 3 | SW | 8 | NW | 18 | NE | 15 | WSW | 6 |
| 7 | ENE | 2 | SW | 7 | ENE | 6 | WNW | 14 | ENE | 3 | SW | 12 | ENE | 10 | WNW | 26 |
| 8 | NE | 12 | SSW | 11 | WSW | 6 | SW | 5 | NE | 19 | SSW | 17 | WSW | 12 | SW | 10 |
| 9 | NE | 10 | SW | 12 | W | 4 | ESE | 1 | NE | 15 | SW | 19 | W | 7 | ESE | 2 |
| 10 | NW | 2 | SW | 9 | ENE | 3 | E | 7 | NW | 3 | SW | 14 | ENE | 6 | E | 14 |
| 11 | SW | 4 | NE | 4 | NE | 1 | SSW | 11 | SW | 6 | NE | 6 | NE | 2 | SSW | 21 |
| 12 | NE | 10 | NNE | 3 | SSW | 1 | S | 7 | NE | 16 | NNE | 5 | SSW | 2 | S | 13 |
| 13 | NE | 11 | S | 5 | ENE | 1 | SSW | 4 | NE | 18 | S | 8 | ENE | 2 | SSW | 8 |
| 14 | NW | 10 | SSW | 7 | NNE | 6 | WSW | 9 | NW | 16 | SSW | 12 | NNE | 12 | WSW | 17 |
| 15 | W | 5 | SW | 6 | ENE | 8 | SW | 4 | W | 8 | SW | 9 | ENE | 16 | SW | 8 |
| 16 | S | 4 | W | 3 | NE | 8 | WSW | 7 | S | 7 | W | 4 | NE | 16 | WSW | 14 |
| 17 | ENE | 4 | ENE | 5 | NE | 2 | WSW | 9 | ENE | 6 | ENE | 8 | NE | 3 | WSW | 17 |
| 18 | SE | 4 | ENE | 6 | SSW | 4 | W | 7 | SE | 5 | ENE | 10 | SSW | 8 | W | 13 |
| 19 | S | 4 | WNW | 7 | SW | 4 | SW | 8 | S | 7 | WNW | 12 | SW | 7 | SW | 14 |
| 20 | SSE | 11 | WNW | 11 | WSW | 2 | E | 4 | SSE | 18 | WNW | 18 | WSW | 4 | E | 7 |
| 21 | WSW | 10 | SSW | 8 | WSW | 13 | S | 13 | WSW | 16 | SSW | 12 | WSW | 24 | S | 25 |
| 22 | NE | 13 | WSW | 9 | WNW | 13 | SSW | 11 | NE | 20 | WSW | 14 | WNW | 26 | SSW | 20 |
| 23 | SSW | 4 | SSW | 3 | NW | 8 | WSW | 12 | SSW | 6 | SSW | 5 | NW | 14 | WSW | 23 |
| 24 | ESE | 4 | W | 5 | WSW | 3 | SSW | 5 | ESE | 6 | W | 8 | WSW | 5 | SSW | 10 |
| 25 | NW | 12 | SW | 7 | WSW | 2 | WNW | 9 | NW | 19 | SW | 11 | WSW | 3 | WNW | 17 |
| 26 | NE | 10 | WSW | 9 | NE | 4 | ENE | 9 | NE | 17 | WSW | 15 | NE | 8 | ENE | 17 |
| 27 | W | 8 | NE | 8 | NW | 1 | WSW | 18 | W | 13 | NE | 13 | NW | 2 | WSW | 33 |
| 28 | ENE | 2 | ENE | 2 | E | 3 | W | 16 | ENE | 4 | ENE | 4 | E | 6 | W | 30 |
| 29 | WSW | 4 | WNW | 1 | S | 6 | WSW | 6 | WSW | 6 | WNW | 1 | S | 12 | WSW | 12 |
| 30 | SSW | 5 | SSW | 6 | NNE | 2 | ENE | 6 | SSW | 8 | SSW | 10 | NNE | 4 | ENE | 10 |
| 31 | | | SW | 8 | E | 4 | | | | | SW | 13 | E | 8 | | |
| Monthly Vector Resultant | NNE | 34 | WSW | 100 | NW | 44 | WSW | 108 | NNE (27°) | 58 | WSW (244°) | 159 | NW (317°) | 66 | WSW (240°) | 204 |
| Daily Vector Mean | NNE | 1.2 | WSW | 3.2 | NW | 1.4 | WSW | 3.6 | NNE | 1.9 | WSW | 5.1 | NW | 2.1 | WSW | 6.8 |

TABLE 31

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1952

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | N | 6 | E | 9 | S | 8[a] | SSE | 6 | N | 10 | E | 14 | S | 16[a] | SSE | 11 |
| 2 | S | 4 | ESE | 4 | WSW | 4[a] | SSW | 8 | S | 7 | ESE | 6 | WSW | 8[a] | SSW | 16 |
| 3 | SSW | 6 | SSW | 8 | SSE | 2[a] | W | 15 | SSW | 10 | SSW | 12 | SSE | 5[a] | W | 30 |
| 4 | W | 3 | W | 7 | S | 4[a] | SW | 12 | W | 4 | W | 11 | S | 7[a] | SW | 22 |
| 5 | SW | 6 | SW | 4 | W | 11 | SSW | 8 | SW | 9 | SW | 6 | W | 20 | SSW | 14 |
| 6 | SW | 12 | ENE | 5 | No Data | | WNW | 9 | SW | 19 | ENE | 8 | No Data | | WNW | 18 |
| 7 | NW | 12 | E | 8 | No Data | | NE | 7 | NW | 20 | E | 12 | No Data | | NE | 14 |
| 8 | SSW | 8 | SE | 6 | E | 10[a] | NE | 6 | SSW | 12 | SE | 12 | E | 20[a] | NE | 10 |
| 9 | W | 10 | NNW | 4 | E | 8[b] | S | 8 | W | 16 | NNW | 6 | E | 15[b] | S | 16 |
| 10 | W | 13 | NNW | 7 | No Data | | SW | 4 | W | 21 | NNW | 11 | No Data | | SW | 9 |
| 11 | NW | 13 | SSW | 8 | WSW | 5[b] | SW | 4 | NW | 21 | SSW | 13 | WSW | 9[b] | SW | 8 |
| 12 | SW | 5 | WSW | 6 | SW | 4 | SW | 2 | SW | 8 | WSW | 10 | SW | 7 | SW | 4 |
| 13 | SE | 1 | SE | 3 | SSW | 6 | WSW | 4 | SE | 1 | SE | 5 | SSW | 10 | WSW | 8 |
| 14 | ENE | 4 | SSW | 8 | SSW | 4 | NE | 6 | ENE | 7 | SSW | 13 | SSW | 8 | NE | 11 |
| 15 | SW | 6 | SW | 12 | SSE | 6 | WSW | 9 | SW | 9 | SW | 18 | SSE | 10 | WSW | 16 |
| 16 | NE | 12 | SW | 1 | W | 2 | WSW | 16 | NE | 19 | SW | 1 | W | 4 | WSW | 30 |
| 17 | WNW | 8 | SE | 4 | NNW | 8 | SW | 11 | WNW | 12 | SE | 7 | NNW | 15 | SW | 20 |
| 18 | WNW | 10 | SW | 10 | ENE | 6 | S | 12 | WNW | 16 | SW | 17 | ENE | 12 | S | 22 |
| 19 | W | 11 | WSW | 10 | S | 2 | SW | 8 | W | 18 | WSW | 17 | S | 4 | SW | 15 |
| 20 | SW | 2 | SSE | 1 | ENE | 5 | SW | 7 | SW | 2 | SSE | 1 | ENE | 9 | SW | 13 |
| 21 | NE | 8 | NW | 2 | SW | 10 | W | 7 | NE | 13 | NW | 3 | SW | 18 | W | 13 |
| 22 | NE | 11 | SSW | 4 | NNW | 12 | SSW | 3 | NE | 18 | SSW | 7 | NNW | 24 | SSW | 6 |
| 23 | ENE | 8 | WSW | 10 | NW | 8 | E | 5 | ENE | 13 | WSW | 16 | NW | 16 | E | 9 |
| 24 | S | 6 | W | 6 | WSW | 5 | W | 6 | S | 10 | W | 10 | WSW | 10 | W | 12 |
| 25 | ESE | 2 | SSE | 1 | WSW | 5 | WSW | 5 | ESE | 3 | SSE | 2 | WSW | 10 | WSW | 9 |
| 26 | WNW | 7 | SSW | 9 | SW | 4 | NW | 8 | WNW | 11 | SSW | 15 | SW | 9 | NW | 14 |
| 27 | NE | 2 | SSW | 6 | NNW | 2 | SSW | 7 | NE | 5 | SSW | 9 | NNW | 4 | SSW | 13 |
| 28 | ENE | 8 | WSW | 7 | ENE | 4 | SSW | 10 | ENE | 12 | WSW | 12 | ENE | 7 | SSW | 18 |
| 29 | NE | 9 | NNE | 7 | S | 6 | WSW | 6 | NE | 14 | NNE | 11 | S | 6 | WSW | 12 |
| 30 | ENE | 11 | S | 2 | NE | 10 | ENE | 1 | ENE | 18 | S | 3 | NE | 20 | ENE | 2 |
| 31 | | | NNW | 7 | E | 8 | | | | | NNW | 11 | E | 16 | | |
| Monthly Vector Resultant | WNW | 53 | SW | 77 | S | 15 | SW | 136 | NW (307°) | 83 | SW (219°) | 126 | SW (218°) | 33 | SW (232°) | 258 |
| Daily Vector Mean | WNW | 1.8 | SW | 2.5 | S | 0.5 | SW | 4.5 | NW | 2.8 | SW | 4.1 | SW | 1.2 | SW | 8.6 |

[a]Based on three observations.
[b]Based on two observations.

TABLE 32

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1953

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNW | 6 | SW | 3 | NE | 6 | S | 3 | NNW | 9 | SW | 5 | NE | 12 | S | 6 |
| 2 | NW | 12 | SSW | 11 | NE | 10 | WSW | 6 | NW | 19 | SSW | 18 | NE | 18 | WSW | 12 |
| 3 | ENE | 2 | W | 8 | NE | 8 | ENE | 5 | ENE | 4 | W | 14 | NE | 16 | ENE | 9 |
| 4 | SE | 3 | SSW | 3 | ENE | 8 | SE | 6 | SE | 4 | SSW | 4 | ENE | 14 | SE | 12 |
| 5 | SSE | 3 | ENE | 6 | NNW | 7 | WNW | 8 | SSE | 5 | ENE | 10 | NNW | 13 | WNW | 15 |
| 6 | WSW | 9 | N | 4 | NE | 7 | SSW | 1 | WSW | 15 | N | 6 | NE | 14 | SSW | 2 |
| 7 | NW | 8 | SW | 11 | NE | 8 | NW | 6 | NW | 13 | SW | 18 | NE | 16 | NW | 12 |
| 8 | NE | 10 | WSW | 5 | E | 6 | NW | 7 | NE | 16 | WSW | 8 | E | 12 | NW | 13 |
| 9 | W | 10 | NW | 8 | N | 5 | SW | 4 | W | 15 | NW | 14 | N | 10 | SW | 7 |
| 10 | WNW | 6 | WNW | 8 | NNW | 3 | ENE | 4 | WNW | 11 | WNW | 13 | NNW | 6 | ENE | 8 |
| 11 | NNW | 5 | SW | 8 | SSW | 5 | SE | 2 | NNW | 8 | SW | 13 | SSW | 10 | SE | 5 |
| 12 | NE | 6 | SSW | 10 | SE | 3 | SSW | 13 | NE | 10 | SSW | 16 | SE | 6 | SSW | 25 |
| 13 | NE | 13 | WSW | 4 | SW | 2 | W | 13 | NE | 21 | WSW | 7 | SW | 5 | W | 25 |
| 14 | NE | 10 | S | 4 | SSE | 7 | W | 7 | NE | 17 | S | 6 | SSE | 13 | W | 14 |
| 15 | ENE | 2 | W | 1 | NW | 10 | SE | 3 | ENE | 4 | W | 2 | NW | 20 | SE | 6 |
| 16 | NE | 10 | W | 5 | W | 5 | WNW | 8 | NE | 16 | W | 8 | W | 10 | WNW | 18 |
| 17 | ENE | 7 | SW | 5 | NW | 11 | WSW | 1 | ENE | 11 | SW | 8 | NW | 21 | WSW | 2 |
| 18 | NW | 3 | N | 1 | NW | 8 | NE | 8 | NW | 5 | N | 1 | NW | 14 | NE | 16 |
| 19 | SSW | 7 | SSW | 4 | NW | 8 | NNE | 2 | SSW | 11 | SSW | 6 | NW | 16 | NNE | 3 |
| 20 | SW | 1 | WSW | 6 | E | 6 | SW | 10 | SW | 2 | WSW | 10 | E | 12 | SW | 18 |
| 21 | WSW | 3 | NE | 3 | E | 7 | WNW | 6 | WSW | 5 | NE | 4 | E | 13 | WNW | 12 |
| 22 | WSW | 6 | NE | 9 | NE | 4 | NW | 8 | WSW | 10 | NE | 14 | NE | 8 | NW | 16 |
| 23 | NW | 13 | W | 5 | WSW | 1 | E | 3 | NW | 21 | W | 8 | WSW | 1 | E | 6 |
| 24 | NNE | 2 | NW | 11 | W | 8 | SSE | 9 | NNE | 3 | NW | 18 | W | 16 | SSE | 18 |
| 25 | NE | 8 | ESE | 5 | WSW | 6 | S | 13 | NE | 12 | ESE | 7 | WSW | 10 | S | 25 |
| 26 | SW | 12 | W | 6 | WSW | 7 | SW | 10 | SW | 20 | W | 9 | WSW | 12 | SW | 19 |
| 27 | SE | 4 | WSW | 5 | WSW | 6 | NW | 7 | SE | 6 | WSW | 8 | WSW | 11 | NW | 13 |
| 28 | S | 2 | SSW | 2 | W | 8 | WSW | 6 | S | 4 | SSW | 3 | W | 16 | WSW | 12 |
| 29 | NE | 3 | SW | 6 | WSW | 7 | ENE | 13 | NE | 5 | SW | 10 | WSW | 13 | ENE | 24 |
| 30 | SSW | 6 | W | 6 | W | 8 | WNW | 3 | SSW | 9 | W | 10 | W | 16 | WNW | 6 |
| 31 | | | NW | 9 | SSW | 2 | | | | | NW | 11 | SSW | 3 | | |
| Monthly Vector Resultant | NNW | 51 | WSW | 103 | NNW | 54 | WSW | 61 | NNW | (341°) 79 | WSW | (255°) 150 | NNW | (332°) 104 | WSW | (248°) 118 |
| Daily Vector Mean | NNW | 1.7 | WSW | 3.3 | NNW | 1.7 | WSW | 2.0 | NNW | 2.6 | WSW | 4.8 | NNW | 3.4 | WSW | 4.0 |

TABLE 33

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1954

| Day of | Daily Mean Land Winds | | | | Daily Mean Over-Water Winds | | | |
|---|---|---|---|---|---|---|---|---|
| Month | June | July | August | September | June | July | August | September |
| 1 | SSE 4 | WNW 3 | WSW 3 | WNW 8 | SSE 7 | WNW 5 | WSW 6 | WNW 15 |
| 2 | W 10 | NW 13 | ENE 2 | SSW 11 | W 17 | NW 21 | ENE 4 | SSW 20 |
| 3 | NE 5 | ESE 3 | SE 2 | W 10 | NE 8 | ESE 4 | SE 4 | W 20 |
| 4 | S 6 | E 4 | SW 2 | ESE 2 | S 10 | E 6 | SW 5 | ESE 4 |
| 5 | SW 11 | NW 10 | NW 7 | W 4 | SW 18 | NW 15 | NW 13 | W 8 |
| 6 | NW 12 | NW 12 | NW 13 | NE 6 | NW 19 | NW 18 | NW 24 | NE 12 |
| 7 | NW 11 | NW 6 | WNW 8 | W 5 | NW 18 | NW 10 | WNW 14 | W 9 |
| 8 | SE 2 | WNW 6 | SSW 6 | NNW 9 | SE 5 | WNW 9 | SSW 11 | NNW 16 |
| 9 | E 8 | NW 4 | ENE 6 | ENE 9 | E 14 | NW 6 | ENE 12 | ENE 18 |
| 10 | S 2 | ENE 4 | WSW 6 | ENE 7 | S 2 | ENE 6 | WSW 12 | ENE 13 |
| 11 | E 2 | ENE 6 | WNW 13 | NW 14 | E 4 | ENE 10 | WNW 24 | NW 28 |
| 12 | NE 6 | E 3 | WNW 9 | ESE 1 | NE 10 | E 5 | WNW 16 | ESE 2 |
| 13 | W 5 | NW 12 | SW 6 | WSW 5 | W 8 | NW 20 | SW 12 | WSW 10 |
| 14 | WSW 3 | W 8 | S 1 | ENE 10 | WSW 4 | W 13 | S 2 | ENE 18 |
| 15 | ESE 11 | NW 13 | S 5 | E 21 | ESE 18 | NW 21 | S 9 | E 40 |
| 16 | E 12 | NNW 8 | W 7 | NE 7 | E 19 | NNW 12 | W 13 | NE 13 |
| 17 | ESE 8 | SSE 2 | WNW 4 | NE 5 | ESE 13 | SSE 4 | WNW 8 | NE 9 |
| 18 | ESE 7 | SW 6 | NNE 2 | E 14 | ESE 12 | SW 9 | NNE 5 | E 26 |
| 19 | SW 4 | NNW 8 | WSW 3 | WSW 6 | SW 6 | NNW 12 | WSW 6 | WSW 10 |
| 20 | SW 7 | S 3 | WSW 4 | WSW 13 | SW 11 | S 5 | WSW 8 | WSW 25 |
| 21 | WNW 2 | N 8 | NE 4 | SW 8 | WNW 4 | N 13 | NE 8 | SW 14 |
| 22 | WSW 7 | NNW 9 | NE 8 | WNW 22 | WSW 11 | NNW 15 | NE 16 | WNW 36 |
| 23 | NW 9 | NW 13 | ENE 7 | W 9 | NW 15 | NW 20 | ENE 13 | W 18 |
| 24 | W 7 | NW 10 | N 1 | NW 1 | W 11 | NW 16 | N 2 | NW 2 |
| 25 | SW 7 | NNE 4 | WSW 4 | WSW 8 | SW 11 | NNE 6 | WSW 8 | WSW 15 |
| 26 | ESE 1 | WSW 2 | NE 7 | WSW 3 | ESE 2 | WSW 4 | NE 13 | WSW 6 |
| 27 | NW 18 | SSW 1 | ESE 2 | SSW 11 | NW 28 | SSW 2 | ESE 5 | SSW 20 |
| 28 | NW 15 | SW 3 | NE 3 | WSW 7 | NW 24 | SW 5 | NE 6 | WSW 13 |
| 29 | NNW 5 | ENE 6 | ENE 9 | NE 14 | NNW 8 | ENE 9 | ENE 18 | NE 26 |
| 30 | E 6 | W 7 | NNE 8 | S 4 | E 10 | W 11 | NNE 15 | S 8 |
| 31 | | NNW 1 | NNW 4 | | | NNW 1 | NNW 8 | |
| Monthly Vector Resultant | WNW 40 | NW 126 | NW 53 | WNW 42 | WNW (290°) 62 | NW (319°) 198 | NW (317°) 93 | WNW (293°) 74 |
| Daily Vector Mean | WNW 1.3 | NW 4.1 | NW 1.7 | WNW 1.4 | WNW 2.1 | NW 6.1 | NW 3.0 | WNW 2.5 |

TABLE 34

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO - 1955

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | N | 12 | WSW | 3 | W | 5 | WSW | 5 | N | 19 | WSW | 5 | W | 9 | WSW | 10 |
| 2 | W | 3 | WSW | 6 | NE | 4 | SW | 1 | W | 4 | WSW | 10 | NE | 7 | SW | 2 |
| 3 | SSE | 2 | NE | 1 | SSW | 3 | NE | 4 | SSE | 5 | NE | 2 | SSW | 6 | NE | 8 |
| 4 | W | 5 | SW | 7 | SW | 5 | SSW | 4 | W | 8 | SW | 11 | SW | 10 | SSW | 8 |
| 5 | WSW | 4 | WSW | 5 | W | 7 | NW | 4 | WSW | 7 | WSW | 8 | W | 13 | NW | 8 |
| 6 | E | 4 | SE | 1 | ESE | 5 | WSW | 7 | E | 7 | SE | 2 | ESE | 10 | WSW | 13 |
| 7 | E | 9 | ESE | 5 | NNW | 10 | NW | 10 | E | 14 | ESE | 8 | NNW | 18 | NW | 20 |
| 8 | E | 16 | E | 8 | NE | 8 | NE | 2 | E | 26 | E | 13 | NE | 16 | NE | 4 |
| 9 | E | 10 | SSE | 4 | E | 10 | E | 11 | E | 16 | SSE | 6 | E | 18 | E | 20 |
| 10 | S | 2 | N | 7 | S | 10 | SSW | 14 | S | 5 | N | 11 | S | 19 | SSW | 26 |
| 11 | E | 8 | NE | 4 | NW | 7 | SE | 1 | E | 13 | NE | 6 | NW | 14 | SE | 1 |
| 12 | SSE | 2 | ENE | 8 | NNE | 10 | NW | 8 | SSE | 2 | ENE | 13 | NNE | 18 | NW | 14 |
| 13 | WNW | 10 | ENE | 5 | NE | 20 | ENE | 10 | WNW | 17 | ENE | 8 | NE | 38 | ENE | 18 |
| 14 | WNW | 5 | SSW | 4 | SSE | 18 | S | 10 | WNW | 8 | SSW | 7 | SSE | 33 | S | 20 |
| 15 | NW | 7 | SSE | 1 | SSW | 11 | W | 2 | NW | 10 | SSE | 2 | SSW | 20 | W | 4 |
| 16 | WNW | 8 | W | 6 | E | 2 | NE | 9 | WNW | 13 | W | 9 | E | 4 | NE | 18 |
| 17 | WSW | 7 | S | 3 | E | 6 | SW | 2 | WSW | 10 | S | 5 | E | 12 | SW | 3 |
| 18 | E | 4 | WNW | 7 | ENE | 5 | ESE | 1 | E | 7 | WNW | 11 | ENE | 9 | ESE | 2 |
| 19 | NNE | 4 | ENE | 5 | W | 5 | SSW | 7 | NNE | 6 | ENE | 8 | W | 10 | SSW | 13 |
| 20 | W | 6 | SSW | 2 | SW | 6 | NW | 12 | W | 9 | SSW | 4 | SW | 10 | NW | 23 |
| 21 | WSW | 8 | WSW | 5 | SSW | 10 | NNW | 2 | WSW | 12 | WSW | 8 | SSW | 19 | NNW | 4 |
| 22 | W | 8 | SW | 5 | SW | 7 | ENE | 14 | W | 13 | SW | 8 | SW | 13 | ENE | 28 |
| 23 | W | 10 | WNW | 10 | NNW | 10 | E | 17 | W | 16 | WNW | 16 | NNW | 18 | E | 32 |
| 24 | NW | 6 | NNE | 6 | ENE | 6 | NW | 4 | NW | 9 | NNE | 9 | ENE | 12 | NW | 8 |
| 25 | NNW | 7 | S | 4 | SSE | 8 | NW | 11 | NNW | 11 | S | 6 | SSE | 15 | NW | 22 |
| 26 | NNW | 6 | SSW | 8 | WSW | 6 | NE | 3 | NNW | 10 | SSW | 13 | WSW | 12 | NE | 5 |
| 27 | SW | 7 | ESE | 2 | SW | 3 | SSE | 12 | SW | 11 | ESE | 4 | SW | 5 | SSE | 22 |
| 28 | SSW | 8 | E | 8 | E | 13 | WNW | 10 | SSW | 13 | E | 14 | E | 25 | WNW | 18 |
| 29 | SSW | 8 | ENE | 8 | E | 12 | ENE | 5 | SSW | 13 | ENE | 12 | E | 24 | ENE | 8 |
| 30 | SW | 9 | ESE | 6 | SSW | 7 | SW | 7 | SW | 14 | ESE | 10 | SSW | 14 | SW | 14 |
| 31 | | | S | 8 | WSW | 13 | | | | | S | 13 | WSW | 25 | | |
| Monthly Vector Resultant | W | 70 | S | 23 | SE | 34 | NNW | 7 | W | (276°) 68 | SSE | (160°) 41 | SE | (142°) 66 | NNE | (22°) 25 |
| Daily Vector Mean | W | 2.3 | S | 0.8 | SE | 1.1 | NNW | 0.2 | W | 2.3 | SSE | 1.3 | SE | 2.1 | NNE | 0.8 |

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO

TABLE 35

| Day of Month | Daily Mean Land Winds—1956 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | NW | 9 | SW | 7 | NW | 6 | SE | 6 |
| 2 | NW | 1 | W | 4 | ENE | 8 | W | 6 |
| 3 | NNW | 3 | ENE | 3 | ESE | 2 | SE | 2 |
| 4 | S | 6 | ENE | 13 | SSE | 3 | SW | 5 |
| 5 | NW | 3 | NE | 14 | ESE | 7 | ENE | 6 |
| 6 | SSE | 3 | ENE | 4 | NE | 10 | WNW | 9 |
| 7 | SW | 6 | SW | 5 | ENE | 3 | NW | 10 |
| 8 | W | 4 | ESE | 6 | WSW | 4 | NW | 10 |
| 9 | SW | 3 | WSW | 6 | SW | 8 | | 0 |
| 10 | N | 5 | WNW | 7 | W | 9 | SW | 6 |
| 11 | SW | 2 | SW | 10 | WSW | 6 | SW | 6 |
| 12 | SW | 9 | WSW | 2 | ESE | 4 | SE | 2 |
| 13 | NW | 9 | E | 5 | WSW | 5 | SSE | 3 |
| 14 | WSW | 8 | NW | 8 | NW | 11 | W | 11 |
| 15 | W | 4 | WNW | 10 | WSW | 4 | NE | 9 |
| 16 | E | 5 | ESE | 2 | SSW | 4 | ENE | 10 |
| 17 | ENE | 4 | NNW | 6 | SSE | 1 | W | 8 |
| 18 | E | 13 | ENE | 3 | E | 2 | NW | 8 |
| 19 | E | 11 | E | 8 | NW | 12 | WSW | 8 |
| 20 | SE | 6 | E | 16 | NW | 11 | WNW | 8 |
| 21 | SSW | 8 | E | 7 | WNW | 7 | WSW | 12 |
| 22 | | 0 | SE | 5 | SW | 6 | ESE | 2 |
| 23 | ENE | 12 | WSW | 8 | SW | 10 | NNE | 6 |
| 24 | SE | 4 | W | 10 | NW | 12 | W | 7 |
| 25 | NW | 12 | WNW | 7 | WSW | 8 | NW | 3 |
| 26 | E | 5 | ENE | 8 | SW | 8 | NE | 8 |
| 27 | SW | 10 | WNW | 5 | S | 3 | E | 12 |
| 28 | W | 10 | WNW | 12 | W | 2 | ENE | 8 |
| 29 | WNW | 8 | NW | 10 | E | 4 | E | 3 |
| 30 | SW | 8 | NW | 10 | ENE | 10 | WSW | 6 |
| 31 | | | WSW | 3 | E | 9 | | |
| Monthly Vector Resultant | WSW | 33 | NNW | 40 | W | 48 | WNW | 50 |
| Daily Vector Mean | WSW | 1.1 | NNW | 1.3 | W | 1.6 | WNW | 1.7 |

TABLE 36

| Day of Month | Daily Mean Land Winds—1957 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | ENE | 1 | WNW | 10 | WNW | 2 | WSW | 1 |
| 2 | NW | 10 | SSW | 4 | SSW | 5 | SE | 4 |
| 3 | NNE | 6 | SSW | 10 | SW | 5 | SW | 12 |
| 4 | SSE | 4 | SW | 2 | NW | 5 | WSW | 13 |
| 5 | NE | 8 | WSW | 16 | WNW | 8 | W | 13 |
| 6 | NE | 8 | SSW | 10 | WNW | 8 | SSW | 7 |
| 7 | WNW | 3 | SW | 6 | SSE | 5 | | 0 |
| 8 | NNE | 6 | ENE | 4 | SSW | 7 | SE | 3 |
| 9 | NE | 11 | W | 11 | SSW | 4 | NE | 10 |
| 10 | NE | 6 | W | 11 | SE | 1 | NE | 6 |
| 11 | ENE | 4 | SW | 8 | WSW | 5 | S | 7 |
| 12 | WNW | 4 | S | 3 | NNW | 6 | ESE | 2 |
| 13 | NE | 6 | E | 2 | NNE | 7 | SSW | 5 |
| 14 | S | 10 | W | 5 | SSE | 3 | W | 1 |
| 15 | S | 8 | NW | 6 | NNW | 1 | E | 4 |
| 16 | S | 4 | SSW | 1 | NW | 5 | SW | 8 |
| 17 | S | 2 | NNE | 1 | SW | 2 | SSW | 2 |
| 18 | | 0 | NNE | 6 | SSE | 2 | NNE | 9 |
| 19 | WSW | 12 | NE | 2 | ENE | 2 | ENE | 3 |
| 20 | SSE | 6 | SSW | 5 | W | 2 | SSW | 3 |
| 21 | SSE | 9 | SW | 10 | NE | 6 | SSE | 3 |
| 22 | NE | 5 | WNW | 8 | NNE | 8 | SW | 5 |
| 23 | S | 8 | NW | 6 | ESE | 1 | WSW | 10 |
| 24 | NNW | 2 | N | 6 | S | 6 | W | 14 |
| 25 | SSW | 6 | WNW | 4 | E | 5 | SW | 9 |
| 26 | SSE | 2 | NE | 6 | W | 6 | NW | 11 |
| 27 | E | 2 | NNE | 6 | NW | 10 | NW | 9 |
| 28 | E | 7 | S | 2 | NE | 10 | SSW | 5 |
| 29 | WSW | 21 | S | 4 | NE | 10 | NNE | 2 |
| 30 | W | 13 | S | 3 | WSW | 2 | SSE | 3 |
| 31 | | | NW | 10 | SW | 4 | | |
| Monthly Vector Resultant | SSW | 14 | W | 94 | NW | 36 | WSW | 75 |
| Daily Vector Mean | SSW | 0.5 | W | 3.0 | NW | 1.2 | WSW | 2.5 |

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TORONTO, ONTARIO

TABLE 37

| Day of Month | Daily Mean Land Winds—1958 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NW | 4 | SSW | 10 | NW | 2 | W | 11 |
| 2 | N | 10 | SW | 11 | SE | 4 | SSE | 2 |
| 3 | NE | 7 | SSW | 2 | SW | 3 | ENE | 6 |
| 4 | ENE | 9 | NE | 9 | NW | 10 | SW | 7 |
| 5 | WNW | 8 | NE | 12 | WSW | 3 | NNE | 5 |
| 6 | NNW | 9 | ENE | 2 | SSW | 6 | S | 4 |
| 7 | SSW | 8 | NE | 5 | SSW | 8 | W | 6 |
| 8 | S | 8 | WNW | 6 | WNW | 8 | NW | 11 |
| 9 | ENE | 6 | SSE | 6 | SW | 8 | SSW | 7 |
| 10 | NE | 8 | ESE | 2 | SW | 8 | W | 12 |
| 11 | SSW | 6 | SSW | 4 | N | 4 | NW | 9 |
| 12 | SSW | 6 | SE | 4 | SSE | 4 | SSW | 4 |
| 13 | N | 2 | ENE | 4 | SSE | 3 | SSW | 8 |
| 14 | W | 12 | NE | 8 | SW | 2 | S | 8 |
| 15 | W | 11 | S | 10 | WSW | 4 | SSW | 8 |
| 16 | W | 16 | W | 9 | WNW | 2 | SW | 1 |
| 17 | WSW | 7 | S | 3 | W | 8 | NE | 10 |
| 18 | ENE | 1 | SSE | 3 | WNW | 7 | NNW | 11 |
| 19 | E | 5 | W | 15 | S | 7 | NE | 1 |
| 20 | E | 4 | NW | 10 | SSW | 6 | NE | 5 |
| 21 | WNW | 6 | NE | 5 | SW | 8 | NE | 7 |
| 22 | SW | 4 | NE | 6 | W | 7 | WSW | 5 |
| 23 | ESE | 9 | SW | 1 | | 0 | SSW | 3 |
| 24 | ENE | 8 | SSE | 3 | NE | 6 | ESE | 2 |
| 25 | ENE | 8 | SSW | 6 | WSW | 9 | SW | 14 |
| 26 | SW | 14 | S | 3 | W | 1 | W | 5 |
| 27 | W | 16 | NNE | 6 | E | 1 | WNW | 2 |
| 28 | SW | 8 | SSE | 2 | NE | 4 | NW | 8 |
| 29 | S | 11 | SW | 11 | ESE | 3 | SSE | 5 |
| 30 | SSW | 10 | SW | 8 | S | 7 | SSE | 18 |
| 31 | | | W | 3 | S | 13 | | |
| Monthly Vector Resultant | WSW | 57 | SW | 34 | SW | 88 | WSW | 64 |
| Daily Vector Mean | WSW | 1.9 | SW | 1.1 | SW | 2.8 | WSW | 2.1 |

TABLE 38

| Day of Month | Daily Mean Land Winds—1959 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | W | 5 | ENE | 10 | WNW | 12 | WNW | 1 |
| 2 | ENE | 2 | NW | 12 | SE | 2 | SE | 5 |
| 3 | WSW | 6 | SW | 5 | ESE | 7 | W | 12 |
| 4 | SSW | 3 | SSW | 4 | ENE | 6 | WSW | 9 |
| 5 | SW | 3 | SSW | 2 | N | 1 | SSE | 3 |
| 6 | NW | 6 | WNW | 5 | E | 12 | ENE | 5 |
| 7 | E | 1 | SW | 7 | E | 4 | SSW | 11 |
| 8 | SW | 7 | SSE | 2 | ENE | 5 | SW | 6 |
| 9 | WSW | 6 | W | 4 | N | 4 | SE | 3 |
| 10 | W | 4 | S | 6 | NW | 9 | NW | 8 |
| 11 | E | 5 | SW | 8 | WNW | 10 | NNW | 8 |
| 12 | SW | 9 | S | 3 | S | 7 | NW | 6 |
| 13 | NW | 13 | ENE | 4 | WSW | 6 | NW | 4 |
| 14 | NW | 14 | ENE | 6 | SSW | 6 | NE | 3 |
| 15 | NW | 16 | ENE | 6 | SSW | 10 | NE | 10 |
| 16 | N | 6 | ENE | 4 | WSW | 8 | N | 9 |
| 17 | E | 3 | SE | 6 | SW | 14 | WNW | 11 |
| 18 | NW | 4 | SSW | 7 | NW | 8 | WNW | 10 |
| 19 | NW | 17 | WNW | 3 | ENE | 2 | SSW | 1 |
| 20 | WNW | 10 | ENE | 11 | SW | 7 | ESE | 5 |
| 21 | WSW | 6 | SSE | 4 | SW | 4 | SW | 13 |
| 22 | NNW | 4 | SSW | 4 | E | 6 | SSE | 2 |
| 23 | WSW | 4 | ESE | 6 | ENE | 14 | SW | 9 |
| 24 | SSE | 1 | WSW | 9 | W | 4 | WNW | 6 |
| 25 | ENE | 8 | NNW | 3 | WSW | 5 | ENE | 6 |
| 26 | SE | 2 | SSW | 5 | SSW | 5 | E | 13 |
| 27 | E | 2 | SSW | 3 | SW | 9 | SSW | 14 |
| 28 | SSW | 7 | SW | 2 | SSW | 4 | SSW | 3 |
| 29 | W | 10 | ENE | 2 | E | 2 | WSW | 6 |
| 30 | WNW | 6 | SSE | 2 | E | 7 | NE | 8 |
| 31 | | | W | 4 | SSE | 2 | | |
| Monthly Vector Resultant | WNW | 106 | S | 34 | SW | 39 | W | 49 |
| Daily Vector Mean | WNW | 3.6 | S | 1.1 | SW | 1.3 | W | 1.7 |

TABLE 39

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1948

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | WNW | 8 | W | 8 | WSW | 8 | WSW | 2 | WNW | 12 | W | 13 | WSW | 16 | WSW | 5 |
| 2 | NE | 2 | W | 9 | SW | 6 | SW | 3 | NE | 3 | W | 14 | SW | 12 | SW | 6 |
| 3 | W | 4 | W | 7 | WSW | 2 | SSW | 2 | W | 6 | W | 11 | WSW | 5 | SSW | 3 |
| 4 | WSW | 7 | WSW | 4 | N | 4 | SE | 1 | WSW | 12 | WSW | 7 | N | 8 | SE | 2 |
| 5 | N | 16 | W | 8 | NE | 13 | ENE | 2 | N | 25 | W | 13 | NE | 25 | ENE | 3 |
| 6 | W | 6 | NNW | 6 | NNW | 6 | S | 4 | W | 10 | NNW | 9 | NNW | 12 | S | 7 |
| 7 | E | 4 | N | 6 | NW | 8 | SSE | 5 | E | 7 | N | 10 | NW | 16 | SSE | 10 |
| 8 | ENE | 8 | W | 6 | W | 6 | SW | 4 | ENE | 13 | W | 10 | W | 6 | SW | 9 |
| 9 | N | 8 | SW | 4 | NW | 4 | NNW | 4 | N | 14 | SW | 6 | NW | 8 | NNW | 6 |
| 10 | WNW | 3 | WSW | 8 | WSW | 5 | WNW | 5 | WNW | 5 | WSW | 12 | WSW | 9 | WNW | 9 |
| 11 | WSW | 6 | SW | 8 | SE | 4 | SW | 5 | WSW | 10 | SW | 13 | SE | 8 | SW | 10 |
| 12 | WSW | 6 | SW | 4 | SW | 7 | SW | 7 | WSW | 10 | SW | 6 | SW | 14 | SW | 13 |
| 13 | W | 9 | NNE | 8 | W | 8 | W | 11 | W | 14 | NNE | 13 | W | 14 | W | 20 |
| 14 | WSW | 7 | NE | 10 | NW | 11 | NNE | 7 | WSW | 11 | NE | 16 | NW | 21 | NNE | 14 |
| 15 | W | 6 | E | 2 | W | 4 | NE | 4 | W | 10 | E | 2 | W | 8 | NE | 8 |
| 16 | W | 5 | S | 3 | SW | 2 | E | 3 | W | 8 | S | 5 | SW | 5 | E | 6 |
| 17 | W | 4 | SW | 11 | ESE | 4 | SW | 8 | W | 6 | SW | 18 | ESE | 8 | SW | 14 |
| 18 | WNW | 6 | W | 11 | S | 8 | SW | 16 | WNW | 10 | W | 18 | S | 15 | SW | 31 |
| 19 | W | 6 | WNW | 4 | WSW | 3 | NE | 4 | W | 10 | WNW | 9 | WSW | 6 | NE | 8 |
| 20 | WSW | 6 | WSW | 5 | WNW | 2 | WNW | 7 | WSW | 10 | WSW | 8 | WNW | 4 | WNW | 14 |
| 21 | WSW | 5 | WSW | 2 | W | 2 | NW | 3 | WSW | 8 | WSW | 4 | W | 3 | NW | 6 |
| 22 | E | 3 | NE | 9 | W | 4 | NNW | 6 | E | 5 | NE | 14 | W | 7 | NNW | 12 |
| 23 | SE | 7 | NW | 6 | SW | 4 | N | 10 | SE | 12 | NW | 10 | SW | 8 | N | 19 |
| 24 | WSW | 11 | WNW | 14 | SW | 8 | NNE | 4 | WSW | 18 | WNW | 23 | SW | 14 | NNE | 7 |
| 25 | WNW | 10 | SW | 10 | SW | 14 | NE | 3 | WNW | 17 | SW | 17 | SW | 27 | NE | 6 |
| 26 | WSW | 3 | SW | 10 | SW | 7 | SW | 2 | WSW | 5 | SW | 17 | SW | 12 | SW | 4 |
| 27 | NE | 1 | W | 6 | SW | 3 | WNW | 2 | NE | 2 | W | 10 | SW | 5 | WNW | 4 |
| 28 | SW | 7 | W | 7 | SSW | 4 | W | 3 | SW | 11 | W | 12 | SSW | 7 | W | 5 |
| 29 | WSW | 11 | WSW | 8 | WNW | 14 | WSW | 2 | WSW | 18 | WSW | 12 | WNW | 26 | WSW | 3 |
| 30 | W | 12 | SSW | 7 | NNW | 7 | SE | 2 | W | 19 | SSW | 11 | NNW | 13 | SE | 3 |
| 31 | | | WNW | 11 | N | 13 | | | | | WNW | 18 | N | 24 | | |
| Monthly Vector Resultant | W | 117 | W | 138 | W | 99 | WSW | 50 | W (272°) | 190 | W (268°) | 219 | W (275°) | 196 | WSW (252°) | 102 |
| Daily Vector Mean | W | 3.9 | W | 4.4 | W | 3.2 | WSW | 1.6 | W | 6.3 | W | 7.1 | W | 6.3 | WSW | 3.4 |

TABLE 40

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1949

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NNE | 1 | SW | 5 | W | 4 | WSW | 12 | NNE | 2 | SW | 8 | W | 8 | WSW | 24 |
| 2 | SE | 1 | SW | 13 | SSE | 2 | SW | 9 | SE | 2 | SW | 21 | SSE | 4 | SW | 18 |
| 3 | SW | 5 | W | 6 | SSW | 2 | W | 2 | SW | 8 | W | 9 | SSW | 4 | W | 5 |
| 4 | SW | 8 | WSW | 8 | W | 4 | SW | 8 | SW | 12 | WSW | 12 | W | 8 | SW | 15 |
| 5 | WNW | 11 | WNW | 3 | W | 7 | WSW | 15 | WNW | 18 | WNW | 5 | W | 14 | WSW | 29 |
| 6 | WSW | 12 | N | 8 | W | 10 | NW | 13 | WSW | 19 | N | 14 | W | 18 | NW | 25 |
| 7 | NW | 15 | NNE | 5 | WSW | 7 | NNE | 8 | NW | 24 | NNE | 8 | WSW | 13 | NNE | 15 |
| 8 | NW | 13 | NE | 8 | SW | 10 | N | 11 | NW | 21 | NE | 12 | SW | 20 | N | 21 |
| 9 | W | 5 | SSW | 6 | WSW | 8 | NW | 10 | W | 8 | SSW | 10 | WSW | 16 | NW | 19 |
| 10 | SW | 4 | WNW | 6 | SW | 8 | W | 5 | SW | 7 | WNW | 10 | SW | 16 | W | 8 |
| 11 | SW | 10 | SSW | 2 | WSW | 6 | E | 3 | SW | 15 | SSW | 4 | WSW | 12 | E | 5 |
| 12 | SW | 10 | NNE | 2 | S | 8 | SSE | 11 | SW | 16 | NNE | 3 | S | 15 | SSE | 21 |
| 13 | SSW | 7 | WNW | 8 | ENE | 6 | SE | 14 | SSW | 11 | WNW | 12 | ENE | 12 | SE | 26 |
| 14 | SSW | 9 | N | 2 | NNW | 2 | WSW | 8 | SSW | 14 | N | 2 | NNW | 4 | WSW | 15 |
| 15 | S | 16 | WSW | 4 | ENE | 9 | W | 4 | S | 26 | WSW | 7 | ENE | 16 | W | 7 |
| 16 | SSE | 10 | SW | 6 | ENE | 8 | SW | 14 | SSE | 16 | SW | 9 | ENE | 13 | SW | 23 |
| 17 | SSE | 10 | S | 4 | W | 1 | SW | 8 | SSE | 17 | S | 6 | W | 2 | SW | 13 |
| 18 | SSE | 9 | S | 2 | NW | 3 | SW | 9 | SSE | 14 | S | 3 | NW | 5 | SW | 15 |
| 19 | NNE | 2 | SW | 11 | N | 16 | WSW | 13 | NNE | 4 | SW | 18 | N | 31 | WSW | 25 |
| 20 | WSW | 2 | WNW | 5 | NW | 15 | WNW | 10 | WSW | 4 | WNW | 8 | NW | 28 | WNW | 20 |
| 21 | SW | 14 | WSW | 3 | WSW | 9 | SSW | 2 | SW | 22 | WSW | 4 | WSW | 18 | SSW | 4 |
| 22 | NW | 14 | WSW | 11 | WSW | 4 | SW | 6 | NW | 22 | WSW | 18 | WSW | 8 | SW | 12 |
| 23 | W | 7 | WNW | 10 | SW | 8 | SW | 2 | W | 11 | WNW | 16 | SW | 15 | SW | 3 |
| 24 | SW | 8 | WSW | 8 | N | 3 | NW | 14 | SW | 13 | WSW | 13 | N | 6 | NW | 28 |
| 25 | S | 3 | NW | 2 | WSW | 4 | WSW | 4 | S | 5 | NW | 4 | WSW | 8 | WSW | 8 |
| 26 | SW | 15 | SSW | 4 | SW | 12 | SE | 6 | SW | 24 | SSW | 7 | SW | 24 | SE | 11 |
| 27 | NW | 8 | SW | 11 | SW | 14 | S | 19 | NW | 13 | SW | 18 | SW | 26 | S | 36 |
| 28 | ENE | 2 | WSW | 11 | WSW | 9 | W | 6 | ENE | 3 | WSW | 18 | WSW | 18 | W | 12 |
| 29 | E | 4 | SW | 11 | NW | 10 | NNW | 7 | E | 6 | SW | 18 | NW | 18 | NNW | 14 |
| 30 | SW | 2 | WNW | 5 | WSW | 8 | WSW | 9 | SW | 3 | WNW | 7 | WSW | 15 | WSW | 18 |
| 31 | | | NW | 16 | SW | 7 | | | | | NW | 26 | SW | 14 | | |
| Monthly Vector Resultant | SW | 136 | W | 134 | WSW | 121 | WSW | 139 | SW (235°) | 216 | WSW (257°) | 225 | WSW (257°) | 236 | WSW (248°) | 262 |
| Daily Vector Mean | SW | 4.5 | W | 4.3 | WSW | 3.9 | WSW | 4.6 | SW | 7.2 | WSW | 7.3 | WSW | 7.6 | WSW | 8.7 |

TABLE 41

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1950

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | WSW | 7 | SW | 10 | ENE | 11 | WNW | 3 | WSW | 11 | SW | 16 | ENE | 21 | WNW | 5 |
| 2 | SW | 8 | SSW | 7 | SW | 11 | N | 11 | SW | 12 | SSW | 11 | SW | 7 | N | 21 |
| 3 | WSW | 14 | WSW | 8 | WSW | 14 | SW | 2 | WSW | 23 | WSW | 13 | WSW | 26 | SW | 3 |
| 4 | W | 17 | SW | 7 | WSW | 10 | WNW | 10 | W | 27 | SW | 11 | WSW | 18 | WNW | 20 |
| 5 | SW | 6 | W | 11 | NNW | 8 | NNW | 10 | SW | 10 | W | 18 | NNW | 16 | NNW | 18 |
| 6 | SW | 14 | WSW | 8 | NNE | 4 | WSW | 6 | SW | 22 | WSW | 12 | NNE | 8 | WSW | 12 |
| 7 | SW | 13 | W | 10 | SW | 3 | WSW | 6 | SW | 21 | W | 16 | SW | 6 | WSW | 12 |
| 8 | SW | 10 | WSW | 6 | SW | 6 | W | 3 | SW | 16 | WSW | 10 | SW | 11 | W | 5 |
| 9 | SW | 10 | WSW | 6 | W | 7 | ENE | 3 | SW | 17 | WSW | 10 | W | 14 | ENE | 5 |
| 10 | WSW | 13 | SSW | 3 | W | 10 | NE | 10 | WSW | 20 | SSW | 5 | W | 18 | NE | 19 |
| 11 | NW | 20 | SE | 6 | N | 8 | NE | 16 | NW | 32 | SE | 9 | N | 16 | NE | 30 |
| 12 | WSW | 8 | SW | 11 | WNW | 3 | NE | 15 | WSW | 12 | SW | 18 | WNW | 6 | NE | 28 |
| 13 | SW | 9 | WSW | 10 | NW | 7 | E | 14 | SW | 15 | WSW | 16 | NW | 12 | E | 26 |
| 14 | SSE | 5 | WSW | 14 | WSW | 7 | SSW | 6 | SSE | 8 | WSW | 22 | WSW | 13 | SSW | 10 |
| 15 | SSW | 4 | S | 3 | SW | 3 | W | 10 | SSW | 7 | S | 4 | SW | 6 | W | 20 |
| 16 | S | 7 | S | 8 | SW | 8 | NW | 12 | S | 12 | S | 12 | SW | 15 | SW | 22 |
| 17 | WNW | 14 | SW | 10 | WSW | 4 | W | 5 | WNW | 22 | SW | 16 | WSW | 7 | W | 9 |
| 18 | WSW | 10 | WNW | 14 | N | 10 | SW | 4 | WSW | 16 | WNW | 22 | N | 19 | SW | 8 |
| 19 | SW | 8 | W | 8 | SSW | 4 | N | 5 | SW | 13 | W | 13 | SSW | 8 | N | 9 |
| 20 | SW | 10 | NNW | 4 | NW | 14 | | 0 | SW | 15 | NNW | 6 | NW | 26 | | 0 |
| 21 | WNW | 12 | W | 8 | WSW | 7 | NE | 4 | WNW | 19 | W | 12 | WSW | 13 | NE | 7 |
| 22 | S | 3 | SW | 7 | SW | 6 | W | 3 | S | 5 | SW | 12 | SW | 12 | W | 5 |
| 23 | SW | 6 | S | 5 | SW | 7 | NW | 17 | SW | 10 | S | 7 | SW | 14 | NW | 31 |
| 24 | WNW | 6 | S | 11 | SW | 4 | NW | 15 | WNW | 10 | S | 18 | SW | 8 | NW | 28 |
| 25 | W | 7 | WSW | 12 | SSW | 12 | W | 1 | W | 11 | WSW | 20 | SSW | 22 | W | 2 |
| 26 | WSW | 8 | WSW | 8 | N | 5 | WSW | 1 | WSW | 13 | WSW | 13 | N | 10 | WSW | 2 |
| 27 | WSW | 10 | SW | 8 | SSW | 2 | NE | 2 | WSW | 15 | SW | 13 | SSW | 4 | NE | 4 |
| 28 | WSW | 10 | SW | 6 | SW | 9 | S | 2 | WSW | 16 | SW | 10 | SW | 18 | S | 4 |
| 29 | SW | 12 | WSW | 12 | ENE | 12 | ESE | 1 | SW | 18 | WSW | 18 | ENE | 22 | ESE | 2 |
| 30 | SSW | 6 | WSW | 10 | ENE | 10 | SW | 4 | SSW | 10 | WSW | 16 | ENE | 18 | SW | 8 |
| 31 | | | E | 2 | W | 3 | | | | | E | 2 | W | 6 | | |
| Monthly Vector Resultant | WSW | 252 | WSW | 210 | W | 90 | NNW | 86 | WSW (244°) | 385 | WSW (238°) | 322 | W (266°) | 172 | NW (325°) | 132 |
| Daily Vector Mean | WSW | 8.4 | WSW | 6.8 | W | 2.9 | NNW | 2.9 | WSW | 12.8 | WSW | 10.4 | W | 5.3 | NW | 4.4 |

TABLE 42

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1951

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | WSW | 4 | SW | 4 | NNW | 10 | NE | 19 | WSW | 7 | SW | 6 | NNW | 18 | NE | 36 |
| 2 | NE | 9 | WSW | 11 | WSW | 4 | NE | 18 | NE | 14 | WSW | 17 | WSW | 7 | NE | 18 |
| 3 | SW | 1 | SW | 5 | WNW | 10 | WNW | 4 | SW | 1 | SW | 8 | WNW | 18 | WNW | 7 |
| 4 | NW | 10 | ENE | 3 | N | 10 | W | 8 | NW | 17 | ENE | 5 | N | 20 | W | 14 |
| 5 | N | 5 | NNW | 13 | NW | 2 | ENE | 2 | N | 8 | NNW | 20 | NW | 4 | ENE | 4 |
| 6 | SW | 4 | NW | 10 | S | 2 | SW | 4 | SW | 7 | NW | 16 | S | 5 | SW | 7 |
| 7 | WNW | 2 | W | 9 | E | 6 | NNE | 2 | WNW | 2 | W | 15 | E | 10 | NNE | 4 |
| 8 | ENE | 2 | SW | 9 | SW | 5 | SW | 8 | ENE | 4 | SW | 15 | SW | 9 | SW | 14 |
| 9 | E | 4 | SSW | 10 | W | 5 | SW | 3 | E | 7 | SSW | 16 | W | 10 | SW | 6 |
| 10 | SE | 13 | SW | 11 | SW | 3 | SE | 7 | SE | 21 | SW | 18 | SW | 6 | SE | 13 |
| 11 | SSE | 7 | NNE | 6 | WSW | 2 | SSW | 14 | SSE | 11 | NNE | 10 | WSW | 4 | SSW | 28 |
| 12 | E | 3 | N | 6 | NW | 2 | SW | 7 | E | 5 | N | 10 | NW | 4 | SW | 13 |
| 13 | SE | 10 | WSW | 8 | SSW | 2 | WSW | 8 | SE | 17 | WSW | 12 | SSW | 4 | WSW | 15 |
| 14 | SE | 6 | SW | 8 | N | 6 | SSW | 6 | SE | 10 | SW | 13 | N | 12 | SSW | 10 |
| 15 | N | 4 | SW | 6 | NNE | 4 | WSW | 7 | N | 6 | SW | 10 | NNE | 7 | WSW | 13 |
| 16 | SW | 6 | SW | 5 | NE | 14 | WSW | 7 | SW | 9 | SW | 8 | NE | 28 | WSW | 13 |
| 17 | SW | 4 | N | 6 | NE | 7 | SW | 9 | SW | 6 | N | 10 | NE | 13 | SW | 17 |
| 18 | SW | 4 | ENE | 4 | NW | 3 | WSW | 8 | SW | 7 | ENE | 7 | NW | 5 | WSW | 14 |
| 19 | SW | 5 | W | 12 | SW | 3 | SW | 4 | SW | 7 | W | 18 | SW | 6 | SW | 8 |
| 20 | S | 8 | W | 12 | SW | 4 | SE | 1 | S | 13 | W | 20 | SW | 8 | SE | 1 |
| 21 | WSW | 14 | SSW | 6 | SW | 12 | SW | 13 | WSW | 22 | SSW | 10 | SW | 22 | SW | 24 |
| 22 | ENE | 6 | WSW | 14 | WNW | 17 | SSW | 10 | ENE | 9 | WSW | 22 | WNW | 32 | SSW | 20 |
| 23 | W | 7 | SW | 4 | WSW | 4 | W | 6 | W | 11 | SW | 6 | WSW | 7 | W | 11 |
| 24 | S | 4 | W | 5 | W | 3 | SSW | 4 | S | 6 | W | 8 | W | 5 | SSW | 8 |
| 25 | NNW | 12 | SW | 7 | WSW | 5 | W | 8 | NNW | 19 | SW | 11 | WSW | 10 | W | 16 |
| 26 | E | 4 | SW | 9 | WSW | 3 | NE | 4 | E | 7 | SW | 14 | WSW | 6 | NE | 8 |
| 27 | W | 6 | N | 5 | WSW | 3 | SW | 16 | W | 9 | N | 9 | WSW | 6 | SW | 31 |
| 28 | WSW | 4 | | 0 | SW | 4 | WSW | 14 | WSW | 6 | | 0 | SW | 7 | WSW | 26 |
| 29 | SW | 9 | WSW | 2 | SW | 4 | WNW | 7 | SW | 14 | WSW | 4 | SW | 8 | WNW | 13 |
| 30 | SW | 8 | SSW | 5 | WSW | 2 | NE | 2 | SW | 13 | SSW | 8 | WSW | 3 | NE | 3 |
| 31 | | | SW | 7 | NE | 5 | | | | | SW | 11 | NE | 9 | | |
| Monthly Vector Resultant | SW | 48 | WSW | 142 | WNW | 68 | SW | 120 | SW | (216°) 101 | WSW | (253°) 224 | WNW | (292°) 126 | SW | (235°) 224 |
| Daily Vector Mean | SW | 1.6 | WSW | 4.6 | WNW | 2.2 | SW | 4.0 | SW | 3.4 | WSW | 7.2 | WNW | 4.1 | SW | 7.5 |

TABLE 43

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1952

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | NW | 5 | SSE | 1 | SSW | 4 | SSE | 4 | NW | 8 | SSE | 2 | SSW | 8 | SSE | 8 |
| 2 | W | 8 | SW | 9 | SW | 8 | SSW | 1 | W | 12 | SW | 15 | SW | 15 | SSW | 2 |
| 3 | SSW | 2 | SW | 6 | WSW | 6 | WSW | 10 | SSW | 4 | SW | 9 | WSW | 11 | WSW | 20 |
| 4 | WNW | 5 | WSW | 11 | SE | 6 | SW | 11 | WNW | 7 | WSW | 18 | SE | 10 | SW | 20 |
| 5 | SW | 4 | WSW | 5 | SW | 10 | S | 6 | SW | 6 | WSW | 8 | SW | 19 | S | 10 |
| 6 | SW | 10 | W | 1 | WSW | 6 | NNW | 7 | SW | 16 | W | 2 | WSW | 12 | NNW | 13 |
| 7 | NW | 8 | SW | 2 | SW | 3 | N | 10 | NW | 14 | SW | 4 | SW | 6 | N | 18 |
| 8 | SW | 2 | SSE | 7 | ENE | 4 | | 0 | SW | 4 | SSE | 10 | ENE | 8 | | 0 |
| 9 | SW | 13 | SW | 8 | SE | 12 | SW | 8 | SW | 20 | SW | 12 | SE | 24 | SW | 16 |
| 10 | WSW | 12 | NNW | 10 | S | 7 | S | 5 | WSW | 19 | NNW | 16 | S | 13 | S | 8 |
| 11 | NW | 10 | SW | 4 | SW | 9 | SW | 4 | NW | 17 | SW | 7 | SW | 18 | SW | 7 |
| 12 | WNW | 2 | WSW | 11 | SW | 5 | SW | 4 | WNW | 4 | WSW | 18 | SW | 9 | SW | 8 |
| 13 | W | 3 | S | 3 | WNW | 12 | SW | 6 | W | 5 | S | 5 | WNW | 24 | SW | 12 |
| 14 | S | 1 | WSW | 8 | SW | 6 | ENE | 5 | S | 2 | WSW | 12 | SW | 10 | ENE | 10 |
| 15 | NW | 8 | WSW | 10 | SSW | 4 | WSW | 5 | NW | 12 | WSW | 14 | SSW | 7 | WSW | 10 |
| 16 | ENE | 5 | WSW | 9 | SW | 6 | WSW | 6 | ENE | 7 | WSW | 14 | SW | 10 | WSW | 12 |
| 17 | WNW | 8 | S | 4 | NNW | 9 | SW | 7 | WNW | 12 | S | 6 | NNW | 18 | SW | 13 |
| 18 | WSW | 10 | SW | 11 | NW | 2 | S | 2 | WSW | 16 | SW | 18 | NW | 3 | S | 5 |
| 19 | WSW | 11 | WNW | 11 | SW | 5 | SW | 10 | WSW | 18 | WNW | 18 | SW | 10 | SW | 20 |
| 20 | SW | 6 | W | 7 | SE | 4 | WSW | 4 | SW | 9 | W | 12 | SE | 8 | WSW | 8 |
| 21 | SE | 2 | SW | 8 | SW | 14 | WSW | 8 | SE | 4 | SW | 13 | SW | 26 | WSW | 15 |
| 22 | ESE | 4 | WSW | 7 | NNW | 14 | S | 3 | ESE | 6 | WSW | 11 | NNW | 27 | S | 5 |
| 23 | SE | 5 | W | 11 | NW | 11 | NE | 5 | SE | 7 | W | 18 | NW | 20 | NE | 9 |
| 24 | SW | 4 | NW | 13 | WNW | 8 | SW | 8 | SW | 6 | NW | 21 | WNW | 15 | SW | 15 |
| 25 | WNW | 6 | W | 5 | SW | 8 | S | 5 | WNW | 10 | W | 8 | SW | 14 | S | 10 |
| 26 | WSW | 7 | SW | 10 | SW | 9 | W | 9 | WSW | 10 | SW | 17 | SW | 18 | W | 18 |
| 27 | NNE | 2 | SW | 9 | SW | 4 | SW | 4 | NNE | 4 | SW | 14 | SW | 7 | SW | 8 |
| 28 | NE | 3 | SW | 12 | SW | 3 | SW | 11 | NE | 5 | SW | 19 | SW | 6 | SW | 20 |
| 29 | ENE | 6 | NNW | 8 | SSW | 9 | SW | 6 | ENE | 10 | NNW | 13 | SSW | 18 | SW | 12 |
| 30 | NE | 10 | SW | 8 | NE | 10 | NW | 4 | NE | 15 | SW | 14 | NE | 20 | NW | 7 |
| 31 | | | WNW | 10 | SE | 10 | | | | | WNW | 16 | SE | 19 | | |
| Monthly Vector Resultant | W | 90 | WSW | 186 | SW | 106 | WSW | 114 | W (266°) | 143 | WSW (250°) | 299 | SW (232°) | 200 | SW (232°) | 222 |
| Daily Vector Mean | W | 3.0 | WSW | 6.0 | SW | 3.4 | WSW | 3.8 | W | 4.8 | WSW | 9.6 | SW | 6.5 | SW | 7.4 |

TABLE 44

LAKE ONTARIO - VECTOR WIND VELOCITIES AT MAIN DUCK ISLAND, ONTARIO - 1953

| Day of Month | Daily Mean Land Winds | | | | | | | Daily Mean Over-Water Winds | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | July | | August | | September | | June | July | | August | | September | |
| 1 | | WSW | 6 | ENE | 4 | SSW | 10 | | WSW | 6 | ENE | 4 | SSW | 10 |
| 2 | | SSW | 12 | NE | 11 | WSW | 15 | | SSW | 12 | NE | 11 | WSW | 15 |
| 3 | | W | 20 | NE | 8 | E | 3 | | W | 20 | NE | 8 | E | 3 |
| 4 | | W | 7 | SSE | 15 | SSE | 18 | | W | 7 | SSE | 15 | SSE | 18 |
| 5 | | S | 8 | N | 14 | SW | 12 | | S | 8 | N | 14 | SW | 12 |
| 6 | | S | 7 | NE | 12 | NE | 4 | | S | 7 | NE | 12 | NE | 4 |
| 7 | | WSW | 20 | SE | 13 | NNW | 8 | | WSW | 20 | SE | 13 | NNW | 8 |
| 8 | | WSW | 13 | SSE | 12 | NNW | 14 | | WSW | 13 | SSE | 12 | NNW | 14 |
| 9 | | W | 18 | NE | 6 | NNW | 5 | | W | 18 | NE | 6 | NNW | 5 |
| 10 | | W | 15 | NE | 22 | ESE | 5 | | W | 15 | NE | 22 | ESE | 5 |
| 11 | | WSW | 14 | S | 1 | S | 12 | | WSW | 14 | S | 1 | S | 12 |
| 12 | | SSW | 11 | S | 8 | S | 28 | | SSW | 11 | S | 8 | S | 28 |
| 13 | | S | 7 | WSW | 8 | WSW | 29 | | S | 7 | WSW | 8 | WSW | 29 |
| 14 | | SSW | 12 | SSW | 7 | W | 27 | | SSW | 12 | SSW | 7 | W | 27 |
| 15 | Data | WSW | 4 | W | 14 | W | 4 | Data | WSW | 4 | W | 14 | W | 4 |
| 16 | Not | E | 14 | W | 15 | SW | 16 | Not | E | 14 | W | 15 | SW | 16 |
| 17 | Available | WNW | 9 | W | 5 | NW | 14 | Available | WNW | 9 | W | 5 | NW | 14 |
| 18 | | SSW | 4 | WNW | 14 | SSE | 12 | | SSW | 4 | WNW | 14 | SSE | 12 |
| 19 | | SSW | 4 | NW | 12 | S | 30 | | SSW | 4 | NW | 12 | S | 30 |
| 20 | | SW | 9 | NE | 5 | S | 26 | | SW | 9 | NE | 5 | S | 26 |
| 21 | | NE | 3 | SE | 1 | SW | 12 | | NE | 3 | SE | 1 | SW | 12 |
| 22 | | ESE | 8 | N | 2 | NW | 18 | | ESE | 8 | N | 2 | NW | 18 |
| 23 | | SW | 13 | W | 8 | N | 8 | | SW | 13 | W | 8 | N | 8 |
| 24 | | NW | 15 | W | 15 | S | 19 | | NW | 15 | W | 15 | S | 19 |
| 25 | | SSE | 8 | WSW | 14 | S | 27 | | SSE | 8 | WSW | 14 | S | 27 |
| 26 | | SSW | 16 | SW | 14 | SW | 20 | | SSW | 16 | SW | 14 | SW | 20 |
| 27 | | WSW | 18 | WSW | 13 | WSW | 11 | | WSW | 18 | WSW | 13 | WSW | 11 |
| 28 | | NW | 8 | WSW | 18 | WNW | 14 | | NW | 8 | WSW | 18 | WNW | 14 |
| 29 | | SSW | 18 | WSW | 15 | NNE | 13 | | SSW | 18 | WSW | 15 | NNE | 13 |
| 30 | | W | 12 | SW | 15 | SSW | 17 | | W | 12 | SW | 15 | SSW | 17 |
| 31 | | WNW | 19 | WSW | 9 | | | | WNW | 19 | WSW | 9 | | |
| Monthly Vector Resultant | | WSW | 232 | WSW | 107 | SW | 240 | | WSW (240°) | 234 | WSW (258°) | 107 | SW (220°) | 240 |
| Daily Vector Mean | | WSW | 7.5 | WSW | 3.5 | SW | 8.0 | | WSW | 7.6 | WSW | 3.5 | SW | 8.0 |

TABLE 45

LAKE ONTARIO - VECTOR WIND VELOCITIES AT MAIN DUCK ISLAND, ONTARIO - 1954

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | S | 15 | S | 6 | WNW | 16 | W | 14 | S | 15 | S | 6 | WNW | 16 | W | 14 |
| 2 | SW | 19 | WSW | 17 | SSW | 6 | SSW | 16 | SW | 19 | WSW | 17 | SSW | 6 | SSW | 16 |
| 3 | WNW | 4 | NW | 10 | SSE | 16 | WSW | 19 | WNW | 4 | NW | 10 | SSE | 16 | WSW | 19 |
| 4 | SSE | 6 | WSW | 4 | WSW | 9 | NNW | 5 | SSE | 6 | WSW | 4 | WSW | 9 | NNW | 5 |
| 5 | SW | 18 | WSW | 6 | NW | 12 | SW | 12 | SW | 18 | WSW | 6 | NW | 12 | SW | 12 |
| 6 | WSW | 19 | WSW | 12 | NW | 8 | NE | 9 | WSW | 19 | WSW | 12 | NW | 8 | NE | 9 |
| 7 | WSW | 20 | WNW | 13 | WNW | 14 | SSW | 10 | WSW | 20 | WNW | 13 | WNW | 14 | SSW | 10 |
| 8 | NNW | 8 | WNW | 11 | ENE | 4 | NNW | 12 | NNW | 8 | WNW | 11 | ENE | 4 | NNW | 12 |
| 9 | ENE | 1 | W | 7 | ENE | 4 | NNE | 11 | ENE | 1 | W | 7 | ENE | 4 | NNE | 11 |
| 10 | SSE | 10 | SSE | 4 | S | 10 | SE | 28 | SSE | 10 | SSE | 4 | S | 10 | SE | 28 |
| 11 | N | 9 | ENE | 1 | W | 26 | NNW | 15 | N | 9 | ENE | 1 | W | 26 | NNW | 15 |
| 12 | ESE | 6 | ESE | 8 | W | 22 | NW | 12 | ESE | 6 | ESE | 8 | W | 22 | NW | 12 |
| 13 | SW | 12 | SW | 19 | WNW | 9 | SSW | 16 | SW | 12 | SW | 19 | WNW | 9 | SSW | 16 |
| 14 | SSW | 6 | WSW | 10 | SW | 2 | NNE | 18 | SSW | 6 | WSW | 10 | SW | 2 | NNE | 18 |
| 15 | NE | 14 | NNW | 18 | SW | 12 | ESE | 10 | NE | 14 | NNW | 18 | SW | 12 | ESE | 10 |
| 16 | SE | 12 | NNW | 11 | SW | 8 | ESE | 10 | SE | 12 | NNW | 11 | SW | 8 | ESE | 10 |
| 17 | SE | 10 | S | 6 | WNW | 18 | N | 10 | SE | 10 | S | 6 | WNW | 18 | N | 10 |
| 18 | SSE | 6 | S | 13 | WNW | 6 | NE | 7 | SSE | 6 | S | 13 | WNW | 6 | NE | 7 |
| 19 | S | 10 | W | 9 | SW | 14 | S | 14 | S | 10 | W | 9 | SW | 14 | S | 14 |
| 20 | S | 14 | SE | 5 | W | 7 | NNW | 10 | S | 14 | SE | 5 | W | 7 | NNW | 10 |
| 21 | SW | 15 | N | 9 | N | 4 | S | 15 | SW | 15 | N | 9 | N | 4 | S | 15 |
| 22 | SSW | 15 | NW | 9 | S | 3 | W | 34 | SSW | 15 | NW | 9 | S | 3 | W | 34 |
| 23 | W | 7 | W | 13 | SSE | 8 | W | 23 | W | 7 | W | 13 | SSE | 8 | W | 23 |
| 24 | W | 10 | NNW | 6 | SW | 16 | WNW | 6 | W | 10 | NNW | 6 | SW | 16 | WNW | 6 |
| 25 | SW | 14 | S | 2 | SW | 12 | SSW | 22 | SW | 14 | S | 2 | SW | 12 | SSW | 22 |
| 26 | S | 2 | SW | 8 | S | 20 | WSW | 12 | S | 2 | SW | 8 | S | 20 | WSW | 12 |
| 27 | WNW | 21 | WSW | 6 | SSE | 4 | SW | 10 | WNW | 21 | WSW | 6 | SSE | 4 | SW | 10 |
| 28 | N | 20 | SW | 5 | NNW | 4 | SW | 14 | N | 20 | SW | 5 | NNW | 4 | SW | 14 |
| 29 | N | 5 | S | 9 | ENE | 8 | SE | 7 | N | 5 | S | 9 | ENE | 8 | SE | 7 |
| 30 | ESE | 3 | WSW | 14 | NE | 16 | S | 17 | ESE | 3 | WSW | 14 | NE | 16 | S | 17 |
| 31 | | | SW | 6 | E | 12 | | | | | SW | 6 | E | 12 | | |
| Monthly Vector Resultant | SW | 148 | WSW | 160 | WSW | 145 | SW | 138 | SW (224°) | 141 | WSW (257°) | 160 | WSW (250°) | 145 | SW (236°) | 138 |
| Daily Vector Mean | SW | 4.9 | WSW | 5.2 | WSW | 4.7 | SW | 4.6 | SW | 4.7 | WSW | 5.2 | WSW | 4.7 | SW | 4.6 |

TABLE 46

LAKE ONTARIO - VECTOR WIND VELOCITIES AT TRENTON, ONTARIO - 1955

| Day of Month | Daily Mean Land Winds | | | | | | | | Daily Mean Over-Water Winds | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | | June | | July | | August | | September | |
| 1 | N | 12 | SW | 14 | SW | 10 | SW | 7 | N | 19 | SW | 22 | SW | 18 | SW | 14 |
| 2 | N | 7 | WSW | 8 | W | 3 | SW | 1 | N | 11 | WSW | 13 | W | 6 | SW | 2 |
| 3 | WSW | 4 | W | 8 | SW | 5 | SW | 4 | WSW | 7 | W | 13 | SW | 10 | SW | 7 |
| 4 | NW | 15 | WSW | 8 | SW | 9 | SW | 5 | NW | 24 | WSW | 13 | SW | 18 | SW | 10 |
| 5 | NW | 12 | SSW | 5 | SW | 10 | WSW | 4 | NW | 18 | SSW | 8 | SW | 20 | WSW | 8 |
| 6 | SW | 6 | WSW | 7 | NE | 5 | WSW | 8 | SW | 9 | WSW | 12 | NE | 9 | WSW | 14 |
| 7 | NE | 2 | WSW | 4 | WNW | 8 | NW | 12 | NE | 3 | WSW | 6 | WNW | 16 | NW | 24 |
| 8 | ENE | 12 | SSW | 2 | NNE | 10 | NNW | 3 | ENE | 19 | SSW | 2 | NNE | 19 | NNW | 5 |
| 9 | SE | 2 | SW | 9 | ESE | 4 | ESE | 7 | SE | 2 | SW | 13 | ESE | 8 | ESE | 13 |
| 10 | SW | 7 | NW | 12 | SSE | 8 | SSW | 14 | SW | 11 | NW | 20 | SSE | 15 | SSW | 28 |
| 11 | SE | 8 | N | 10 | WNW | 3 | NW | 4 | SE | 12 | N | 15 | WNW | 5 | NW | 7 |
| 12 | SW | 5 | NE | 8 | NE | 5 | NW | 11 | SW | 8 | NE | 12 | NE | 10 | NW | 21 |
| 13 | W | 13 | SSW | 3 | NE | 19 | E | 4 | W | 21 | SSW | 5 | NE | 36 | E | 8 |
| 14 | W | 7 | SW | 8 | SSE | 8 | SSE | 6 | W | 11 | SW | 13 | SSE | 15 | SSE | 10 |
| 15 | WNW | 7 | SSE | 3 | WSW | 7 | NNW | 2 | WNW | 12 | SSE | 5 | WSW | 13 | NNW | 3 |
| 16 | SW | 9 | SW | 11 | SW | 6 | ENE | 6 | SW | 14 | SW | 18 | SW | 11 | ENE | 11 |
| 17 | W | 7 | WSW | 8 | SW | 4 | SW | 4 | W | 12 | WSW | 13 | SW | 7 | SW | 8 |
| 18 | WSW | 5 | WNW | 6 | SW | 4 | SSW | 4 | WSW | 8 | WNW | 10 | SW | 7 | SSW | 8 |
| 19 | SW | 2 | NNW | 2 | WNW | 6 | SW | 8 | SW | 3 | NNW | 4 | WNW | 10 | SW | 16 |
| 20 | WSW | 5 | SW | 7 | SW | 9 | NW | 14 | WSW | 8 | SW | 11 | SW | 18 | NW | 28 |
| 21 | SW | 6 | WSW | 8 | WSW | 12 | NW | 4 | SW | 10 | WSW | 12 | WSW | 23 | NW | 7 |
| 22 | WSW | 13 | SW | 9 | WSW | 8 | ENE | 5 | WSW | 20 | SW | 14 | WSW | 14 | ENE | 10 |
| 23 | WSW | 11 | WSW | 11 | N | 11 | ESE | 6 | WSW | 18 | WSW | 18 | N | 20 | ESE | 12 |
| 24 | W | 6 | NE | 7 | WNW | 1 | NNE | 4 | W | 9 | NE | 11 | WNW | 2 | NNE | 7 |
| 25 | W | 6 | SW | 5 | SW | 3 | NW | 8 | W | 9 | SW | 8 | SW | 6 | NW | 14 |
| 26 | NW | 7 | SW | 7 | SW | 7 | W | 2 | NW | 12 | SW | 11 | SW | 13 | W | 3 |
| 27 | W | 7 | NE | 4 | SSE | 7 | SE | 7 | W | 11 | NE | 6 | SSE | 13 | SE | 13 |
| 28 | WSW | 8 | NE | 13 | E | 3 | W | 9 | WSW | 12 | NE | 20 | E | 5 | W | 18 |
| 29 | SW | 8 | SE | 2 | E | 4 | SE | 3 | SW | 12 | SE | 4 | E | 7 | SE | 6 |
| 30 | SW | 13 | SSW | 3 | SSW | 5 | SSW | 8 | SW | 21 | SSW | 4 | SSW | 10 | SSW | 16 |
| 31 | | | SW | 8 | SW | 14 | | | | | SW | 13 | SW | 27 | | |
| Monthly Vector Resultant | W | 140 | WSW | 112 | SW | 78 | WSW | 67 | W | (265°) 224 | WSW | (246°) 189 | SW | (231°) 147 | WSW | (251°) 111 |
| Daily Vector Mean | W | 4.7 | WSW | 3.6 | SW | 2.5 | WSW | 2.2 | W | 7.5 | WSW | 6.1 | SW | 4.8 | WSW | 3.7 |

LAKE SUPERIOR - VECTOR WIND VELOCITIES AT DULUTH, MINNESOTA

TABLE 47

| Day of Month | Daily Mean Land Winds—1950 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | WSW | 11 | S | 6 | N | 8 | NNW | 6 |
| 2 | NW | 15 | E | 3 | N | 3 | SE | 3 |
| 3 | NW | 15 | SE | 5 | ENE | 3 | NW | 11 |
| 4 | W | 9 | NW | 10 | E | 5 | N | 2 |
| 5 | W | 12 | NW | 5 | E | 4 | S | 6 |
| 6 | E | 16 | NW | 6 | E | 8 | SW | 10 |
| 7 | SSW | 10 | SW | 6 | S | 6 | SSW | 8 |
| 8 | SE | 11 | SSE | 10 | WSW | 8 | NW | 4 |
| 9 | WSW | 14 | SSE | 5 | W | 6 | ENE | 14 |
| 10 | WNW | 16 | ESE | 3 | ENE | 6 | ENE | 22 |
| 11 | WNW | 4 | SE | 6 | ESE | 3 | ENE | 26 |
| 12 | SSW | 8 | W | 14 | ENE | 4 | ENE | 10 |
| 13 | NW | 6 | WNW | 16 | E | 5 | NW | 8 |
| 14 | ESE | 5 | ESE | 6 | S | 6 | NW | 8 |
| 15 | SSE | 7 | ESE | 7 | WSW | 5 | NNW | 5 |
| 16 | NE | 4 | WSW | 6 | NE | 1 | ENE | 10 |
| 17 | SE | 4 | ESE | 4 | N | 2 | S | 3 |
| 18 | ESE | 5 | WNW | 4 | SE | 6 | SW | 5 |
| 19 | W | 15 | ENE | 9 | WNW | 18 | ENE | 10 |
| 20 | NW | 10 | SE | 4 | WSW | 12 | SSW | 4 |
| 21 | S | 5 | SSW | 6 | NW | 10 | ENE | 15 |
| 22 | SE | 12 | SW | 4 | SSW | 11 | WNW | 14 |
| 23 | W | 11 | WNW | 1 | NNW | 3 | N | 8 |
| 24 | NW | 4 | NW | 8 | ENE | 4 | WSW | 9 |
| 25 | E | 16 | NW | 6 | NE | 8 | WSW | 12 |
| 26 | WNW | 16 | W | 4 | ESE | 6 | SSW | 10 |
| 27 | WSW | 5 | W | 5 | WSW | 2 | SSE | 12 |
| 28 | NW | 16 | W | 5 | ENE | 6 | SW | 12 |
| 29 | WNW | 17 | WSW | 8 | E | 8 | WSW | 2 |
| 30 | NNW | 8 | E | 14 | S | 5 | ENE | 10 |
| 31 | | | NE | 15 | WNW | 4 | | |
| Monthly Vector Resultant | W | 116 | WSW | 26 | ENE | 8 | NE | 34 |
| Daily Vector Mean | W | 3.9 | WSW | 0.8 | ENE | 0.3 | NE | 1.1 |

TABLE 48

| Day of Month | Daily Mean Land Winds—1951 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NE | 15 | W | 7 | E | 12 | NE | 11 |
| 2 | ENE | 29 | SW | 4 | WSW | 8 | NNW | 3 |
| 3 | NE | 8 | ENE | 18 | NE | 6 | NW | 5 |
| 4 | SW | 5 | NE | 10 | ESE | 6 | NE | 4 |
| 5 | WSW | 5 | SSW | 2 | E | 11 | ESE | 7 |
| 6 | ENE | 11 | SSE | 10 | E | 8 | WNW | 11 |
| 7 | ENE | 14 | SW | 9 | E | 5 | SW | 3 |
| 8 | ESE | 8 | WSW | 13 | W | 13 | S | 6 |
| 9 | W | 10 | W | 15 | NW | 10 | SE | 7 |
| 10 | WNW | 8 | NW | 5 | E | 7 | W | 12 |
| 11 | NE | 6 | WSW | 6 | NNW | 5 | S | 4 |
| 12 | E | 10 | W | 10 | NE | 4 | WNW | 13 |
| 13 | E | 9 | WSW | 14 | ENE | 6 | SW | 18 |
| 14 | SE | 4 | SSW | 10 | ENE | 8 | W | 16 |
| 15 | SW | 7 | ENE | 13 | ENE | 12 | WNW | 11 |
| 16 | SSW | 8 | ENE | 18 | ENE | 10 | WSW | 9 |
| 17 | NNW | 8 | ENE | 7 | ENE | 8 | NW | 10 |
| 18 | ESE | 1 | W | 14 | SSE | 6 | WSW | 10 |
| 19 | SSE | 5 | WNW | 9 | W | 8 | E | 18 |
| 20 | NW | 15 | SE | 6 | W | 5 | W | 1 |
| 21 | W | 6 | W | 12 | NNW | 12 | WSW | 13 |
| 22 | ESE | 6 | WNW | 8 | NW | 4 | W | 9 |
| 23 | WNW | 2 | WNW | 6 | S | 4 | ESE | 1 |
| 24 | SE | 2 | SW | 10 | SSE | 12 | W | 10 |
| 25 | E | 11 | SW | 14 | SE | 8 | NNW | 3 |
| 26 | SSW | 2 | NW | 7 | WSW | 11 | ENE | 8 |
| 27 | S | 13 | ENE | 10 | SSW | 3 | W | 21 |
| 28 | WSW | 17 | SW | 7 | NNE | 2 | WNW | 8 |
| 29 | WSW | 15 | SSW | 12 | ENE | 12 | SE | 10 |
| 30 | NNW | 16 | SW | 12 | ENE | 28 | S | 5 |
| 31 | | | WNW | 13 | NE | 24 | | |
| Monthly Vector Resultant | ENE | 34 | WSW | 109 | ENE | 112 | W | 111 |
| Daily Vector Mean | ENE | 1.1 | WSW | 3.5 | ENE | 3.6 | W | 3.7 |

LAKE SUPERIOR - VECTOR WIND VELOCITIES AT DULUTH, MINNESOTA

TABLE 49

| Day of Month | Daily Mean Land Winds—1952 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | WSW | 6 | SE | 8 | WSW | 8 | W | 18 |
| 2 | S | 8 | SSE | 11 | NE | 10 | NW | 13 |
| 3 | NW | 11 | W | 17 | ENE | 19 | WSW | 15 |
| 4 | SSW | 7 | WSW | 10 | N | 9 | SSW | 8 |
| 5 | SW | 10 | S | 10 | SW | 7 | ESE | 8 |
| 6 | WNW | 10 | SE | 12 | NNW | 2 | ENE | 16 |
| 7 | E | 10 | NW | 10 | ESE | 5 | ESE | 12 |
| 8 | W | 14 | WSW | 4 | SE | 6 | SSE | 9 |
| 9 | W | 18 | WSW | 3 | WNW | 11 | ESE | 8 |
| 10 | WNW | 12 | ESE | 7 | SW | 12 | SE | 8 |
| 11 | E | 11 | W | 6 | E | 11 | SSW | 10 |
| 12 | E | 8 | E | 11 | SW | 12 | SSE | 8 |
| 13 | S | 8 | WNW | 10 | SSW | 11 | SE | 10 |
| 14 | WSW | 8 | NW | 6 | S | 11 | WSW | 14 |
| 15 | ENE | 10 | SSE | 4 | N | 2 | W | 13 |
| 16 | SW | 3 | E | 8 | N | 1 | WNW | 5 |
| 17 | WSW | 21 | SSW | 8 | WNW | 7 | W | 8 |
| 18 | WNW | 10 | S | 6 | SSW | 9 | WNW | 16 |
| 19 | W | 10 | ENE | 2 | SSE | 6 | WNW | 12 |
| 20 | ESE | 4 | E | 8 | WSW | 6 | W | 10 |
| 21 | ENE | 10 | SW | 10 | NNE | 3 | NW | 6 |
| 22 | ENE | 14 | WSW | 24 | E | 7 | NNW | 9 |
| 23 | SE | 9 | W | 18 | S | 6 | NE | 2 |
| 24 | E | 4 | S | 13 | SSW | 9 | S | 6 |
| 25 | NNW | 8 | SSW | 10 | S | 10 | WNW | 10 |
| 26 | NW | 2 | WSW | 12 | SE | 10 | SSW | 4 |
| 27 | ENE | 8 | SSW | 9 | E | 8 | WSW | 16 |
| 28 | ENE | 13 | NW | 14 | NW | 14 | W | 11 |
| 29 | ENE | 14 | SW | 6 | ENE | 16 | S | 4 |
| 30 | ENE | 12 | W | 10 | SE | 12 | SW | 8 |
| 31 | | | SW | 9 | W | 10 | | |
| Monthly Vector Resultant | NW | 6 | SW | 142 | S | 57 | WSW | 121 |
| Daily Vector Mean | NW | 0.2 | SW | 4.6 | S | 1.9 | WSW | 4.0 |

TABLE 50

| Day of Month | Daily Mean Land Winds—1953 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | SE | 5 | E | 9 | E | 14 | W | 10 |
| 2 | S | 6 | NW | 15 | E | 15 | E | 13 |
| 3 | E | 14 | SSW | 6 | E | 12 | W | 13 |
| 4 | E | 16 | WSW | 5 | NNE | 7 | W | 18 |
| 5 | NW | 7 | W | 8 | ENE | 9 | WSW | 14 |
| 6 | SSE | 10 | W | 15 | W | 3 | WNW | 10 |
| 7 | ESE | 9 | WNW | 17 | NW | 10 | WNW | 4 |
| 8 | ENE | 4 | WNW | 10 | N | 6 | E | 13 |
| 9 | N | 5 | NNW | 5 | S | 2 | ESE | 8 |
| 10 | E | 5 | W | 10 | SE | 5 | SSE | 6 |
| 11 | E | 6 | SSW | 10 | SSW | 7 | NW | 9 |
| 12 | WNW | 7 | S | 6 | W | 12 | N | 19 |
| 13 | ENE | 6 | ESE | 3 | SW | 10 | NE | 4 |
| 14 | S | 7 | E | 6 | NW | 13 | SE | 4 |
| 15 | S | 6 | ESE | 6 | NW | 11 | WNW | 15 |
| 16 | NE | 5 | SE | 5 | NW | 6 | W | 3 |
| 17 | ESE | 3 | SE | 2 | SE | 2 | ESE | 13 |
| 18 | ESE | 8 | WSW | 3 | N | 4 | WNW | 10 |
| 19 | ENE | 13 | SW | 5 | N | 1 | WSW | 13 |
| 20 | SE | 12 | E | 7 | W | 8 | WNW | 15 |
| 21 | WSW | 25 | SSE | 2 | WSW | 7 | WNW | 13 |
| 22 | WNW | 15 | W | 18 | SSW | 5 | SW | 2 |
| 23 | E | 8 | NW | 12 | SW | 8 | S | 10 |
| 24 | E | 11 | SSE | 6 | S | 7 | S | 2 |
| 25 | WSW | 18 | SE | 3 | SSE | 8 | W | 13 |
| 26 | WSW | 21 | NW | 6 | SSW | 12 | SSW | 2 |
| 27 | NNE | 2 | NNE | 2 | SW | 12 | WSW | 9 |
| 28 | WNW | 4 | SSW | 7 | S | 6 | NW | 4 |
| 29 | SSE | 7 | WNW | 10 | SSW | 8 | E | 19 |
| 30 | E | 5 | W | 8 | WSW | 8 | W | 14 |
| 31 | | | E | 6 | SSW | 10 | | |
| Monthly Vector Resultant | SE | 60 | W | 92 | SW | 62 | W | 106 |
| Daily Vector Mean | SE | 2.0 | W | 3.0 | SW | 2.0 | W | 3.6 |

LAKE SUPERIOR - VECTOR WIND VELOCITIES AT DULUTH, MINNESOTA

TABLE 51

| Day of Month | Daily Mean Land Winds—1954 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NNW | 14 | NW | 10 | W | 10 | SW | 8 |
| 2 | ENE | 10 | ENE | 15 | WNW | 9 | E | 16 |
| 3 | NE | 8 | E | 14 | WNW | 13 | NE | 3 |
| 4 | SE | 3 | WNW | 9 | NW | 11 | NE | 5 |
| 5 | ESE | 4 | NW | 4 | NW | 14 | WNW | 4 |
| 6 | E | 16 | E | 4 | ENE | 6 | E | 6 |
| 7 | ESE | 11 | E | 7 | ESE | 2 | WNW | 16 |
| 8 | SSW | 19 | ENE | 5 | NW | 6 | ENE | 5 |
| 9 | WSW | 11 | E | 11 | NNW | 2 | E | 9 |
| 10 | NNE | 10 | E | 18 | N | 11 | NNW | 8 |
| 11 | E | 25 | E | 12 | N | 4 | ENE | 9 |
| 12 | W | 6 | WNW | 11 | SSW | 6 | ENE | 19 |
| 13 | S | 5 | WSW | 5 | SSW | 10 | ENE | 25 |
| 14 | ESE | 11 | NW | 12 | W | 7 | ENE | 24 |
| 15 | S | 8 | NW | 5 | WSW | 8 | ENE | 18 |
| 16 | S | 2 | S | 4 | NNE | 6 | ESE | 15 |
| 17 | SW | 6[a] | WSW | 9 | SE | 6 | NE | 4 |
| 18 | NNW | 6[a] | WNW | 7 | WSW | 6 | E | 11 |
| 19 | ENE | 11 | WSW | 10 | NW | 8 | W | 19 |
| 20 | WNW | 8 | NE | 8 | E | 7 | W | 6 |
| 21 | SSE | 4 | E | 14 | E | 13 | NW | 19 |
| 22 | WNW | 11 | ESE | 12 | SE | 12 | NW | 8 |
| 23 | SSE | 8 | NW | 7 | WSW | 10 | SE | 8 |
| 24 | W | 6 | SW | 2 | SW | 13 | WSW | 4 |
| 25 | NNE | 5 | SSW | 5 | NE | 9 | W | 13 |
| 26 | WNW | 12 | SSW | 8 | E | 14 | WNW | 9 |
| 27 | ENE | 11 | SW | 5 | ESE | 10 | WSW | 12 |
| 28 | ESE | 14 | E | 10 | WNW | 3 | E | 6 |
| 29 | SW | 11 | WSW | 11 | NW | 10 | E | 6 |
| 30 | WNW | 19 | NNW | 2 | ENE | 6 | NNW | 14 |
| 31 | | | WNW | 8 | SW | 4 | | |
| Monthly Vector Resultant | ESE | 42 | NE | 23 | WNW | 46 | NE | 96 |
| Daily Vector Mean | ESE | 1.4 | NE | 0.7 | WNW | 1.5 | NE | 3.2 |

[a]Based on three observations.

TABLE 52

| Day of Month | Daily Mean Land Winds—1955 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | E | 12 | W | 10 | E | 7 | W | 8 |
| 2 | SE | 12 | WNW | 1 | ESE | 8 | S | 12 |
| 3 | ESE | 11 | SW | 8 | SE | 9 | SSW | 14 |
| 4 | S | 7 | E | 2 | WNW | 5 | WNW | 12 |
| 5 | SE | 7 | ESE | 4 | SE | 8 | W | 6 |
| 6 | SSE | 6 | ESE | 6 | WNW | 5 | NW | 12 |
| 7 | NW | 10 | ESE | 9 | ENE | 5 | ENE | 4 |
| 8 | NW | 5 | WSW | 12 | SSE | 8 | E | 14 |
| 9 | E | 6 | WNW | 13 | SSW | 10 | E | 7 |
| 10 | N | 9 | ENE | 10 | WNW | 13 | WNW | 19 |
| 11 | ENE | 10 | ENE | 17 | E | 1 | WNW | 11 |
| 12 | NNE | 11 | ESE | 14 | S | 8 | SSE | 5 |
| 13 | NW | 10 | SSW | 11 | SE | 7 | SSE | 14 |
| 14 | NE | 2 | WNW | 12 | SE | 6 | NW | 6 |
| 15 | SW | 6 | N | 16 | WNW | 8 | E | 18 |
| 16 | SW | 8 | NE | 7 | ESE | 6 | SSW | 6 |
| 17 | SE | 10 | NNW | 2 | SE | 3 | ESE | 15 |
| 18 | SSE | 12 | ENE | 9 | SW | 6 | SSE | 8 |
| 19 | SW | 9 | SE | 8 | SW | 12 | WNW | 14 |
| 20 | W | 13 | S | 9 | SSW | 2 | NE | 11 |
| 21 | WNW | 17 | S | 9 | WNW | 10 | E | 20 |
| 22 | NW | 16 | W | 6 | WNW | 8 | SSW | 4 |
| 23 | WNW | 14 | NNW | 13 | ESE | 4 | WNW | 10 |
| 24 | ENE | 4 | WNW | 4 | S | 8 | WNW | 14 |
| 25 | WNW | 3 | SSW | 14 | ENE | 4 | NE | 4 |
| 26 | ENE | 3 | ESE | 6 | E | 14 | SE | 8 |
| 27 | SW | 8 | ENE | 18 | ENE | 19 | WSW | 8 |
| 28 | S | 10 | E | 18 | E | 6 | S | 1 |
| 29 | SSW | 13 | SE | 8 | NE | 2 | WSW | 14 |
| 30 | SE | 9 | SE | 7 | WNW | 18 | WNW | 10 |
| 31 | | | SSE | 5 | NW | 16 | | |
| Monthly Vector Resultant | SW | 33 | WNW | 56 | SSE | 29 | WSW | 42 |
| Daily Vector Mean | SW | 1.1 | WNW | 1.8 | SSE | 0.9 | WSW | 1.4 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT DULUTH, MINNESOTA

TABLE 53

| Day of Month | Daily Mean Land Winds—1956 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NW | 11 | NNW | 7 | ENE | 13 | W | 14 |
| 2 | SSW | 8 | NW | 10 | E | 13 | S | 8 |
| 3 | E | 12 | ENE | 13 | E | 16 | W | 7 |
| 4 | ENE | 11 | E | 12 | E | 7 | NW | 8 |
| 5 | E | 14 | SW | 6 | N | 3 | NW | 7 |
| 6 | ESE | 14 | N | 6 | W | 10 | WNW | 15 |
| 7 | W | 12 | ENE | 16 | WSW | 5 | W | 13 |
| 8 | W | 9 | NE | 8 | SW | 7 | NE | 7 |
| 9 | WNW | 8 | NW | 13 | NW | 14 | SE | 10 |
| 10 | SSE | 3 | WNW | 12 | W | 12 | ESE | 6 |
| 11 | S | 6 | WSW | 5 | NW | 9 | ESE | 2 |
| 12 | SSW | 12 | E | 14 | S | 9 | NW | 5 |
| 13 | SW | 6 | NNW | 2 | W | 14 | WNW | 9 |
| 14 | SW | 9 | SW | 9 | W | 14 | NNW | 9 |
| 15 | ENE | 16 | ESE | 10 | WSW | 5 | ESE | 7 |
| 16 | ENE | 26 | E | 10 | ESE | 6 | W | 12 |
| 17 | ENE | 16 | E | 7 | E | 3 | WNW | 13 |
| 18 | ENE | 14 | E | 10 | NW | 9 | W | 7 |
| 19 | ESE | 8 | ENE | 16 | WNW | 12 | NNW | 12 |
| 20 | NW | 12 | ENE | 9 | WNW | 10 | WNW | 2 |
| 21 | SSW | 2 | N | 3 | SSE | 5 | E | 16 |
| 22 | E | 11 | NNW | 3 | E | 14 | ENE | 14 |
| 23 | SE | 10 | W | 10 | NNW | 9 | WSW | 12 |
| 24 | NNW | 7 | WNW | 14 | WNW | 9 | SSE | 1 |
| 25 | ESE | 5 | W | 5 | WSW | 13 | E | 14 |
| 26 | NW | 5 | SSW | 3 | E | 12 | E | 14 |
| 27 | NW | 14 | WNW | 12 | E | 8 | SE | 10 |
| 28 | W | 7 | NNW | 7 | E | 18 | SW | 14 |
| 29 | ESE | 7 | S | 1 | SE | 8 | SSE | 12 |
| 30 | SSE | 6 | SSE | 6 | E | 14 | SSW | 5 |
| 31 | | | W | 9 | SSW | 10 | | |
| Monthly Vector Resultant | E | 56 | NNE | 62 | N | 25 | W | 38 |
| Daily Vector Mean | E | 1.9 | NNE | 2.0 | N | 0.8 | W | 1.3 |

TABLE 54

| Day of Month | Daily Mean Land Winds—1957 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NW | 14 | SE | 5 | SSE | 5 | ESE | 7 |
| 2 | SSE | 5 | WSW | 9 | W | 8 | ESE | 5 |
| 3 | WNW | 8 | W | 10 | WNW | 14 | N | 12 |
| 4 | NNE | 5 | W | 9 | NNW | 16 | NE | 7 |
| 5 | E | 14 | WNW | 15 | W | 5 | SW | 5 |
| 6 | ESE | 9 | W | 12 | SSW | 9 | NNW | 3 |
| 7 | E | 7 | E | 10 | SSW | 15 | NW | 2 |
| 8 | ESE | 12 | WNW | 16 | SW | 6 | SSW | 9 |
| 9 | SE | 10 | NW | 12 | N | 6 | SSW | 3 |
| 10 | SW | 5 | SE | 9 | WSW | 2 | SW | 13 |
| 11 | WNW | 13 | SE | 7 | E | 9 | SW | 10 |
| 12 | ESE | 8 | ENE | 7 | E | 18 | W | 7 |
| 13 | SSE | 6 | NW | 8 | SW | 5 | WNW | 12 |
| 14 | SSE | 7 | ENE | 20 | WSW | 5 | SW | 9 |
| 15 | WSW | 15 | ENE | 18 | NNW | 8 | WSW | 16 |
| 16 | NE | 9 | E | 12 | NNW | 9 | WNW | 15 |
| 17 | E | 16 | E | 9 | WNW | 7 | SSE | 10 |
| 18 | WSW | 14 | SE | 10 | NW | 9 | E | 9 |
| 19 | W | 10 | NNE | 5 | W | 12 | N | 9 |
| 20 | SSE | 5 | ESE | 8 | ENE | 5 | ESE | 5 |
| 21 | SE | 12 | NNW | 6 | E | 12 | N | 7 |
| 22 | SE | 7 | ENE | 13 | N | 1 | E | 14 |
| 23 | NNE | 7 | E | 13 | NNW | 12 | WNW | 12 |
| 24 | E | 7 | SE | 9 | NE | 5 | WSW | 1 |
| 25 | E | 6 | SSW | 8 | SSW | 9 | WNW | 9 |
| 26 | SW | 13 | WSW | 2 | NW | 15 | NE | 7 |
| 27 | SSW | 6 | SE | 3 | E | 14 | SE | 7 |
| 28 | W | 8 | SE | 6 | ENE | 12 | SSW | 10 |
| 29 | WNW | 16 | NW | 9 | E | 5 | SSW | 14 |
| 30 | NW | 14 | W | 2 | E | 14 | WNW | 14 |
| 31 | | | WNW | 5 | E | 15 | | |
| Monthly Vector Resultant | S | 30 | ENE | 30 | N | 37 | WSW | 70 |
| Daily Vector Mean | S | 1.0 | ENE | 1.0 | N | 1.2 | WSW | 2.3 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT DULUTH, MINNESOTA

TABLE 55

| Day of Month | Daily Mean Land Winds—1958 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | ENE | 8 | ESE | 5 | SSW | 10 | ESE | 9 |
| 2 | E | 12 | W | 9 | SW | 13 | SE | 12 |
| 3 | E | 9 | ENE | 13 | N | 7 | NW | 6 |
| 4 | E | 1 | ENE | 18 | SE | 9 | W | 3 |
| 5 | NW | 15 | E | 8 | WSW | 12 | ENE | 14 |
| 6 | SW | 9 | SW | 8 | WSW | 14 | N | 7 |
| 7 | SW | 13 | NW | 12 | NW | 8 | WNW | 14 |
| 8 | E | 3 | NE | 5 | SE | 7 | SSE | 2 |
| 9 | SSE | 6 | E | 12 | SW | 13 | NW | 9 |
| 10 | WNW | 12 | WNW | 8 | E | 7 | N | 6 |
| 11 | W | 13 | WSW | 7 | SSW | 7 | S | 8 |
| 12 | SW | 12 | E | 7 | WNW | 14 | WSW | 2 |
| 13 | NW | 14 | SE | 12 | SSW | 9 | E | 13 |
| 14 | NW | 7 | SW | 13 | W | 15 | SSW | 12 |
| 15 | NW | 10 | NW | 14 | NNW | 9 | WSW | 15 |
| 16 | N | 5 | W | 7 | WSW | 13 | WNW | 7 |
| 17 | ESE | 5 | SSW | 14 | NNW | 9 | E | 12 |
| 18 | E | 7 | W | 16 | ESE | 8 | SE | 9 |
| 19 | W | 5 | NNW | 1 | NE | 5 | S | 12 |
| 20 | WNW | 15 | SSE | 5 | NW | 12 | S | 14 |
| 21 | WSW | 7 | SW | 9 | WNW | 14 | WSW | 15 |
| 22 | WSW | 6 | SW | 12 | WSW | 3 | SSW | 15 |
| 23 | SSW | 7 | SSW | 9 | SSE | 7 | S | 17 |
| 24 | WNW | 12 | SW | 9 | NW | 16 | S | 5 |
| 25 | WNW | 10 | W | 16 | SW | 9 | W | 15 |
| 26 | NW | 18 | S | 7 | W | 5 | WSW | 10 |
| 27 | W | 9 | ESE | 6 | SSE | 8 | W | 9 |
| 28 | S | 9 | W | 14 | N | 5 | SSW | 6 |
| 29 | SW | 9 | W | 15 | E | 14 | SW | 9 |
| 30 | E | 17 | WNW | 10 | N | 9 | WNW | 23 |
| 31 | | | SSE | 2 | NW | 16 | | |
| Monthly Vector Resultant | W | 98 | WSW | 96 | W | 114 | SW | 113 |
| Daily Vector Mean | W | 3.3 | WSW | 3.1 | W | 3.7 | SW | 3.8 |

TABLE 56

| Day of Month | Daily Mean Land Winds—1959 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | W | 9 | W | 6 | ENE | 10 | E | 12 |
| 2 | SW | 10 | SW | 6 | ESE | 8 | SW | 12 |
| 3 | ESE | 8 | SSW | 18 | S | 3 | WSW | 14 |
| 4 | SSW | 12 | SW | 10 | SSE | 3 | WSW | 5 |
| 5 | NNW | 4 | WNW | 12 | SSE | 8 | SE | 13 |
| 6 | E | 9 | WSW | 1 | NW | 12 | S | 6 |
| 7 | SSW | 15 | SSE | 12 | NNE | 11 | W | 9 |
| 8 | SSW | 16 | SW | 7 | ENE | 9 | ENE | 19 |
| 9 | SW | 6 | W | 16 | ENE | 5 | SW | 17 |
| 10 | E | 10 | WNW | 12 | W | 7 | WNW | 16 |
| 11 | SW | 7 | NW | 10 | NNE | 3 | SSW | 9 |
| 12 | W | 22 | WNW | 4 | NW | 10 | NE | 3 |
| 13 | NNW | 8 | SE | 7 | E | 9 | E | 8 |
| 14 | ESE | 9 | ESE | 8 | WSW | 11 | ENE | 19 |
| 15 | ENE | 20 | S | 12 | SSW | 5 | NE | 14 |
| 16 | E | 19 | S | 10 | SSE | 9 | NE | 5 |
| 17 | E | 11 | WNW | 11 | W | 12 | WNW | 10 |
| 18 | ESE | 6 | NNW | 10 | ESE | 10 | NNE | 4 |
| 19 | WNW | 11 | ESE | 2 | SSE | 12 | SSE | 12 |
| 20 | W | 7 | SSW | 11 | S | 9 | S | 12 |
| 21 | NW | 8 | NW | 4 | E | 10 | N | 4 |
| 22 | WNW | 13 | SE | 10 | ENE | 16 | ENE | 14 |
| 23 | W | 1 | WNW | 15 | WSW | 8 | WSW | 14 |
| 24 | ENE | 13 | NNW | 8 | SW | 4 | WSW | 7 |
| 25 | E | 7 | S | 9 | SSE | 8 | E | 12 |
| 26 | ENE | 8 | SSE | 5 | N | 1 | SSW | 11 |
| 27 | SE | 9 | S | 10 | ENE | 13 | SSW | 12 |
| 28 | SW | 12 | S | 10 | ENE | 5 | SW | 16 |
| 29 | WNW | 14 | SSW | 9 | ENE | 10 | WSW | 10 |
| 30 | NNW | 5 | WNW | 11 | N | 7 | NW | 12 |
| 31 | | | WNW | 13 | NE | 11 | | |
| Monthly Vector Resultant | SSW | 28 | SW | 139 | E | 74 | SSW | 62 |
| Daily Vector Mean | SSW | 0.9 | SW | 4.5 | E | 2.5 | SSW | 2.1 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT PORT ARTHUR, ONTARIO

TABLE 57

| Day of Month | Daily Mean Land Winds—1950 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | W | 12 | E | 4 | NNE | 14 | W | 5 |
| 2 | WNW | 14 | W | 5 | NW | 8 | S | 2 |
| 3 | WNW | 16 | E | 4 | W | 2 | WNW | 10 |
| 4 | N | 4 | NE | 5 | SW | 6 | WSW | 6 |
| 5 | E | 7 | WNW | 2 | WSW | 7 | SW | 3 |
| 6 | E | 3 | WSW | 6 | SW | 8 | SW | 6 |
| 7 | NE | 4 | WSW | 8 | NE | 3 | SW | 6 |
| 8 | ENE | 9 | WNW | 2 | WNW | 4 | WNW | 6 |
| 9 | WNW | 5 | NE | 7 | WNW | 8 | SW | 8 |
| 10 | WNW | 14 | WNW | 2 | WNW | 8 | W | 13 |
| 11 | SSE | 4 | E | 1 | SW | 8 | W | 13 |
| 12 | WSW | 3 | WNW | 3 | WSW | 7 | WSW | 8 |
| 13 | WNW | 4 | WNW | 16 | SW | 8 | W | 5 |
| 14 | SW | 8 | S | 5 | E | 4 | W | 8 |
| 15 | NE | 9 | E | 7 | W | 4 | W | 10 |
| 16 | NW | 11 | W | 5 | SSE | 4 | WSW | 5 |
| 17 | W | 4 | WSW | 4 | WNW | 7 | W | 5 |
| 18 | SW | 3 | WNW | 7 | SW | 10 | W | 6 |
| 19 | WSW | 5 | ESE | 2 | SW | 16 | WSW | 8 |
| 20 | NW | 9 | NNE | 1 | SW | 13 | W | 8 |
| 21 | WSW | 8 | WSW | 6 | NW | 10 | WSW | 8 |
| 22 | E | 6 | WNW | 1 | SW | 13 | WSW | 13 |
| 23 | SW | 8 | ESE | 6 | WSW | 14 | Anemograph Out of Order | |
| 24 | E | 13 | W | 1 | NNW | 6 | | |
| 25 | NE | 7 | WSW | 5 | SSW | 7 | | |
| 26 | WNW | 9 | W | 6 | S | 3 | | |
| 27 | W | 8 | WSW | 7 | WSW | 6 | | |
| 28 | WNW | 12 | WSW | 9 | E | 6 | | |
| 29 | WSW | 7 | ENE | 3 | SSW | 5 | | |
| 30 | NW | 13 | E | 8 | SW | 4 | | |
| 31 | | | ENE | 4 | WNW | 8 | | |
| Monthly Vector Resultant | WNW | 110 | W | 43 | WSW | 140 | WSW | 152[b] 204[c] |
| Daily Vector Mean | WNW | 3.7 | W | 1.4 | WSW | 4.5 | WSW | 6.9[b] |

TABLE 58

| Day of Month | Daily Mean Land Winds—1951 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NE | 6 | ESE | 6 | S | 4 | SE | 3 |
| 2 | E | 10 | W | 6 | WNW | 11 | SW | 3 |
| 3 | NE | 13 | ESE | 3 | NE | 7 | W | 8 |
| 4 | WSW | 10 | E | 2 | SW | 5 | S | 2 |
| 5 | WSW | 4 | W | 7 | SSE | 4 | SE | 3 |
| 6 | SSE | 2 | WSW | 10 | ESE | 8 | SSW | 9 |
| 7 | SE | 6 | W | 5 | ESE | 5 | W | 9 |
| 8 | SE | 6 | W | 10 | NW | 11 | W | 9 |
| 9 | NW | 9 | NW | 12 | NW | 10 | ESE | 4 |
| 10 | WNW | 9 | WNW | 7 | SSE | 4 | S | 6 |
| 11 | SSE | 4 | SW | 8 | N | 3 | W | 9 |
| 12 | ESE | 4 | WNW | 10 | SW | 4 | E | 2 |
| 13 | SW | 6 | WNW | 8 | SW | 2 | WSW | 16 |
| 14 | NW | 2 | ESE | 5 | WSW | 2[a] | W | 16 |
| 15 | ENE | 5 | SSE | 2 | E | 1 | NW | 6 |
| 16 | SW | 7 | SSE | 3 | S | 2 | W | 9 |
| 17 | WSW | 6 | SSW | 3 | SSW | 2 | NW | 9 |
| 18 | SSW | 3 | NW | 12 | W | 6 | W | 7 |
| 19 | E | 6 | NW | 12 | W | 1[a] | SE | 6 |
| 20 | NNE | 9 | WSW | 6 | WSW | 3 | SSE | 3 |
| 21 | SSE | 5 | NW | 13 | NNE | 6 | W | 10 |
| 22 | SE | 5 | NW | 3 | W | 4 | E | 5 |
| 23 | S | 4 | W | 6 | W | 8 | SW | 2 |
| 24 | WSW | 2 | WSW | 6 | SSW | 4 | W | 9 |
| 25 | ESE | 7 | NNE | 3 | ESE | 6 | W | 8 |
| 26 | E | 6 | SSE | 2 | W | 8 | ESE | 18 |
| 27 | E | 8 | ESE | 4 | W | 6 | NW | 20 |
| 28 | W | 4 | NNW | 2 | SSW | 2 | NW | 15 |
| 29 | E | 12 | SSW | 7 | E | 4 | SSE | 4 |
| 30 | W | 4 | WNW | 2 | E | 8 | SW | 3 |
| 31 | | | NW | 15 | NE | 14 | | |
| Monthly Vector Resultant | ESE | 42 | WNW | 118 | W | 22 | W | 116 |
| Daily Vector Mean | ESE | 1.4 | WNW | 3.8 | W | 0.7 | W | 3.9 |

[a]Based on two readings.
[b]Based on 22 days.
[c]Based on 30 days.

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT PORT ARTHUR, ONTARIO

TABLE 59

| Day of Month | Daily Mean Land Winds—1952 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NW | 10 | E | 6 | SSE | 8 | WSW | 12 |
| 2 | ESE | 6 | ESE | 7 | WSW | 3 | NNW | 10 |
| 3 | NW | 12 | SE | 13 | ESE | 3 | SW | 7 |
| 4 | SW | 10 | WNW | 15 | NNE | 2 | SSE | 4 |
| 5 | NW | 7 | SE | 3 | NW | 10 | NE | 2 |
| 6 | NW | 9 | SE | 2 | SSW | 2 | E | 3 |
| 7 | SE | 8 | N | 5 | SW | 6 | SSE | 4 |
| 8 | SW | 6[a] | SSE | 2 | ENE | 2 | S | 3 |
| 9 | NW | 22 | SE | 6 | NW | 4 | S | 3 |
| 10 | NW | 6 | E | 7 | W | 9 | SSE | 4 |
| 11 | NNE | 10 | SSW | 3 | WNW | 11 | ESE | 5 |
| 12 | SSE | 4 | ESE | 6 | WNW | 9 | E | 6 |
| 13 | SE | 10 | WNW | 4 | NW | 1 | SE | 4 |
| 14 | NW | 10 | SW | 1 | ENE | 6 | W | 6 |
| 15 | SE | 6 | | 0 | NNW | 7 | WNW | 9 |
| 16 | SE | 1 | ESE | 7 | WSW | 2 | WNW | 7 |
| 17 | WNW | 18 | W | 4 | SW | 3 | NW | 7 |
| 18 | NW | 10 | NW | 2 | SW | 10 | WNW | 10 |
| 19 | NW | 14 | W | 5 | WSW | 9 | NW | 6 |
| 20 | ESE | 4 | ESE | 7 | NNW | 5 | ENE | 4 |
| 21 | S | 4 | WNW | 9 | N | 5 | N | 1 |
| 22 | SE | 6 | E | 4 | SW | 5 | NW | 4 |
| 23 | ESE | 7 | NW | 11 | W | 5 | W | 2 |
| 24 | SSE | 6 | WSW | 10 | | 0 | WSW | 8 |
| 25 | SE | 3 | NNE | 3 | SW | 6 | NNW | 12 |
| 26 | S | 2 | W | 9 | NNW | 2 | NW | 7 |
| 27 | SE | 9 | SSW | 6 | SSE | 3 | E | 3 |
| 28 | SE | 11 | NNW | 12 | NNW | 9 | NNE | 8 |
| 29 | SE | 14 | SW | 12 | SE | 4 | SSE | 5 |
| 30 | SE | 8 | NW | 15 | ESE | 4 | WSW | 4 |
| 31 | | | WSW | 10 | SW | 12 | | |
| Monthly Vector Resultant | W | 33 | W | 39 | W | 70 | WNW | 54 |
| Daily Vector Mean | W | 1.1 | W | 1.3 | W | 2.3 | WNW | 1.8 |

[a]Based on three readings.

TABLE 60

| Day of Month | Daily Mean Land Winds—1953 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | W | 5 | ENE | 6 | E | 8 | WNW | 5 |
| 2 | S | 1 | NW | 11 | E | 8 | E | 5 |
| 3 | E | 8 | WSW | 8 | E | 4 | WSW | 8 |
| 4 | E | 16 | SSE | 2 | ENE | 6 | WSW | 14 |
| 5 | NNE | 10 | WSW | 13 | ENE | 6 | W | 17 |
| 6 | NW | 5 | W | 8 | E | 10 | W | 7 |
| 7 | S | 4 | W | 18 | E | 8 | W | 8 |
| 8 | NNE | 12 | NW | 13 | NW | 4 | SSW | 2 |
| 9 | NW | 6 | WNW | 6 | S | 2 | E | 4 |
| 10 | ESE | 3 | WSW | 10 | SE | 4 | | 0 |
| 11 | ENE | 6 | SW | 8 | ESE | 4 | NW | 7 |
| 12 | NNE | 2 | ESE | 5 | W | 11 | N | 16 |
| 13 | SE | 1 | E | 6 | SSW | 7 | WSW | 6 |
| 14 | E | 5 | E | 5 | WNW | 11 | | 0 |
| 15 | NE | 5 | ENE | 6 | W | 10 | NW | 4 |
| 16 | ENE | 5 | ESE | 4 | W | 5 | E | 4 |
| 17 | ESE | 4 | E | 1 | WNW | 3 | E | 10 |
| 18 | NE | 9 | SSW | 5 | WNW | 2 | NNW | 7 |
| 19 | ENE | 4 | SSW | 7 | WSW | 7 | WSW | 6 |
| 20 | E | 14 | ESE | 4 | SSE | 2 | W | 11 |
| 21 | W | 28 | ESE | 6 | E | 5 | WNW | 9 |
| 22 | WNW | 21 | W | 14 | NW | 4 | W | 2 |
| 23 | SW | 8 | WNW | 12 | W | 9 | SSW | 6 |
| 24 | ENE | 7 | SSW | 6 | SSW | 2 | WNW | 6 |
| 25 | WSW | 8 | ESE | 2 | ESE | 3 | SE | 2 |
| 26 | W | 25 | W | 7 | S | 2 | E | 10 |
| 27 | NE | 2 | W | 4 | WNW | 4 | WNW | 6 |
| 28 | SW | 6 | WSW | 8 | S | 4 | NW | 5 |
| 29 | SSE | 4 | WNW | 10 | ESE | 2 | E | 10 |
| 30 | E | 2 | W | 9 | W | 6 | WSW | 16 |
| 31 | | | ENE | 3 | SW | 7 | | |
| Monthly Vector Resultant | NNW | 34 | W | 104 | WSW | 21 | W | 92 |
| Daily Vector Mean | NNW | 1.1 | W | 3.3 | WSW | 0.7 | W | 3.1 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT PORT ARTHUR, ONTARIO

TABLE 61

| Day of Month | Daily Mean Land Winds—1954 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | NE | 12 | WNW | 9 | SSW | 2 | ESE | 3 |
| 2 | ENE | 5 | | 0 | WNW | 3 | WNW | 9 |
| 3 | NE | 5 | E | 3 | WNW | 10 | W | 4 |
| 4 | SSE | 2 | NE | 4 | WSW | 6 | E | 2 |
| 5 | SSW | 6 | W | 5 | N | 5 | SW | 2 |
| 6 | SE | 3 | ENE | 6 | WSW | 5 | NE | 8 |
| 7 | E | 12 | NW | 1 | SW | 6 | NNW | 6 |
| 8 | S | 5 | SW | 3 | E | 3 | SW | 2 |
| 9 | WNW | 8 | ESE | 4 | NNW | 2 | ESE | 2 |
| 10 | WSW | 2 | ENE | 7 | NNW | 7 | WNW | 3 |
| 11 | ENE | 10 | E | 7 | NNW | 2 | ENE | 3 |
| 12 | SW | 2 | NW | 12 | WSW | 5 | SSE | 2 |
| 13 | SE | 4 | WSW | 9 | S | 3 | ENE | 5 |
| 14 | ENE | 7 | NW | 5 | WNW | 2 | NE | 10 |
| 15 | ENE | 10 | SW | 6 | W | 5 | ENE | 5 |
| 16 | E | 7 | SSE | 2 | N | 8 | SE | 4 |
| 17 | NE | 6 | WNW | 3 | SSW | 6 | E | 2 |
| 18 | NW | 8 | WNW | 6 | E | 5 | ENE | 5 |
| 19 | SSE | 4 | SE | 3 | WNW | 4 | W | 18 |
| 20 | NW | 7 | ENE | 2 | SSW | 4 | WSW | 5 |
| 21 | SSE | 2 | ESE | 3 | E | 6 | NNW | 6 |
| 22 | NW | 6 | SE | 1 | SSE | 4 | WNW | 7 |
| 23 | S | 4 | NE | 4 | W | 8 | SSE | 4 |
| 24 | NW | 6 | ESE | 3 | SW | 4 | N | 1 |
| 25 | E | 3 | SW | 4 | NNE | 3 | W | 6 |
| 26 | NW | 12 | NE | 1 | S | 3 | W | 6 |
| 27 | SE | 3 | NE | 2 | E | 3 | NW | 10 |
| 28 | E | 7 | E | 5 | E | 8 | ESE | 5 |
| 29 | E | 5 | W | 7 | E | 2 | E | 9 |
| 30 | N | 3 | WSW | 9 | SSE | 1 | NW | 5 |
| 31 | | | SW | 2 | WSW | 4 | | |
| Monthly Vector Resultant | ENE | 58 | WNW | 21 | W | 26 | NW | 44 |
| Daily Vector Mean | ENE | 2.0 | WNW | 0.7 | W | 0.8 | NW | 1.5 |

TABLE 62

| Day of Month | Daily Mean Land Winds—1955 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | June | | July | | August | | September | |
| 1 | ENE | 5 | W | 6 | S | 4 | WSW | 7 |
| 2 | E | 8 | ESE | 6 | E | 3 | SW | 4 |
| 3 | ENE | 8 | NE | 4 | SSW | 4 | WSW | 8 |
| 4 | NE | 10 | NNE | 2 | NNW | 5 | WNW | 13 |
| 5 | E | 6 | E | 3 | SSW | 2 | SW | 9 |
| 6 | E | 9 | NE | 4 | W | 4 | WNW | 13 |
| 7 | ENE | 4 | NE | 7 | NW | 6 | WSW | 2 |
| 8 | ENE | 4 | SW | 5 | SW | 6 | ENE | 3 |
| 9 | E | 7 | WNW | 16 | S | 2 | SE | 4 |
| 10 | N | 6 | S | 3 | W | 9 | W | 18 |
| 11 | NNE | 11 | E | 4 | SW | 4 | W | 10 |
| 12 | NNE | 4 | E | 5 | SE | 1 | WSW | 5 |
| 13 | WNW | 5 | SSE | 4 | E | 2 | SE | 4 |
| 14 | SSW | 5 | W | 4 | SW | 4 | N | 2 |
| 15 | WSW | 6 | N | 7 | ENE | 3 | ESE | 6 |
| 16 | SSW | 8 | ENE | 5 | SW | 2 | ENE | 6 |
| 17 | SSE | 6 | W | 2 | W | 8 | ENE | 6 |
| 18 | ESE | 6 | ESE | 5 | WNW | 3 | ENE | 5 |
| 19 | E | 3 | NW | 2 | N | 2 | E | 11 |
| 20 | WSW | 4 | WSW | 6 | W | 4 | WNW | 1 |
| 21 | W | 10 | S | 1 | NW | 8 | E | 16 |
| 22 | WNW | 13 | W | 13 | WSW | 4 | E | 11 |
| 23 | NNW | 1 | WNW | 8 | S | 4 | W | 7 |
| 24 | NW | 2 | SSW | 8 | SSW | 8 | WNW | 8 |
| 25 | S | 1 | WSW | 4 | W | 3 | WSW | 6 |
| 26 | SW | 5 | NE | 6 | E | 3 | SW | 4 |
| 27 | SW | 10 | ENE | 7 | ENE | 8 | NW | 2 |
| 28 | S | 5 | E | 4 | NE | 6 | SW | 6 |
| 29 | NE | 3 | E | 8 | WNW | 4 | WSW | 8 |
| 30 | SW | 2 | WSW | 2 | WNW | 14 | WNW | 8 |
| 31 | | | SE | 2 | NW | 16 | | |
| Monthly Vector Resultant | NE | 26 | NNW | 12 | W | 69 | W | 60 |
| Daily Vector Mean | NE | 0.9 | NNW | 0.4 | W | 2.2 | W | 2.0 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT PORT ARTHUR, ONTARIO

TABLE 63

| Day of Month | Daily Mean Land Winds—1956 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | WNW | 4 | WNW | 8 | SSE | 3 | WSW | 8 |
| 2 | ENE | 5 | NW | 4 | E | 4 | WSW | 4 |
| 3 | ENE | 5 | ESE | 3 | E | 4 | WSW | 4 |
| 4 | SE | 4 | ENE | 7 | ENE | 8 | WSW | 4 |
| 5 | ESE | 2 | E | 5 | E | 1 | E | 2 |
| 6 | E | 8 | WNW | 6 | SE | 2 | WNW | 12 |
| 7 | NW | 6 | E | 4 | WSW | 7 | W | 9 |
| 8 | WSW | 9 | NE | 12 | SSW | 2 | WNW | 1 |
| 9 | WNW | 10 | NNW | 11 | N | 2 | SW | 1 |
| 10 | NNE | 6 | WSW | 11 | W | 9 | ENE | 4 |
| 11 | W | 4 | ESE | 2 | S | 4 | SSW | 4 |
| 12 | WSW | 6 | ESE | 4 | WNW | 1 | NE | 3 |
| 13 | E | 7 | NNE | 6 | WNW | 7 | N | 4 |
| 14 | WSW | 7 | WSW | 9 | NW | 10 | NNW | 5 |
| 15 | ENE | 7 | E | 8 | WSW | 6 | SE | 4 |
| 16 | E | 7 | E | 3 | WSW | 2 | NW | 4 |
| 17 | E | 8 | SSE | 2 | NNE | 1 | WNW | 10 |
| 18 | E | 8 | E | 3 | W | 7 | NNW | 4 |
| 19 | E | 8 | E | 6 | W | 8 | NNW | 8 |
| 20 | WSW | 3 | E | 2 | SW | 6 | W | 9 |
| 21 | W | 8 | NNE | 1 | W | 6 | SW | 4 |
| 22 | W | 4 | SW | 2 | E | 2 | E | 4 |
| 23 | ENE | 8 | SW | 8 | NNE | 3 | S | 1 |
| 24 | NNE | 8 | WNW | 8 | WSW | 8 | ESE | 2 |
| 25 | SW | 6 | WSW | 8 | W | 11 | E | 6 |
| 26 | ENE | 6 | SW | 2 | ESE | 4 | ENE | 4 |
| 27 | NW | 12 | WNW | 12 | WNW | 3 | ESE | 7 |
| 28 | W | 10 | NW | 10 | NE | 13 | ESE | 7 |
| 29 | NE | 3 | W | 6 | W | 10 | NW | 15 |
| 30 | ENE | 6 | WSW | 5 | E | 2 | SSW | 5 |
| 31 | | | NW | 8 | SE | 5 | | |
| Monthly Vector Resultant | NE | 34 | NW | 50 | W | 54 | WNW | 48 |
| Daily Vector Mean | NE | 1.1 | NW | 1.6 | W | 1.8 | WNW | 1.6 |

TABLE 64

| Day of Month | Daily Mean Land Winds—1957 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | NW | 19 | SW | 4 | SW | 1 | E | 7 |
| 2 | SW | 6 | SW | 5 | W | 7 | E | 5 |
| 3 | NW | 8 | WNW | 10 | WNW | 12 | NE | 12 |
| 4 | ESE | 6 | WNW | 4 | NW | 11 | N | 5 |
| 5 | NE | 8 | WNW | 18 | W | 7 | SW | 6 |
| 6 | ENE | 3 | W | 4 | W | 3 | W | 2 |
| 7 | SSW | 6 | ENE | 4 | NNW | 2 | W | 6 |
| 8 | E | 7 | W | 12 | W | 8 | SSW | 3 |
| 9 | E | 5 | NW | 14 | WSW | 4 | SSW | 4 |
| 10 | NE | 6 | ESE | 3 | WSW | 8 | SW | 4 |
| 11 | W | 7 | E | 4 | NNE | 5 | SSW | 6 |
| 12 | ESE | 4 | E | 3 | SE | 3 | WSW | 4 |
| 13 | ENE | 8 | W | 4 | SSW | 2 | W | 8 |
| 14 | ENE | 12 | ENE | 5 | W | 8 | WSW | 6 |
| 15 | WSW | 19 | ESE | 3 | WNW | 1 | SW | 4 |
| 16 | WSW | 4 | E | 6 | WNW | 7 | WNW | 11 |
| 17 | ENE | 8 | ENE | 3 | WNW | 8 | SE | 3 |
| 18 | SW | 7 | E | 6 | WSW | 5 | NNE | 4 |
| 19 | W | 11 | E | 1 | W | 9 | NNE | 5 |
| 20 | S | 4 | ESE | 5 | E | 6 | S | 4 |
| 21 | ENE | 8 | W | 4 | ESE | 3 | N | 2 |
| 22 | NE | 5 | ENE | 3 | SSW | 6 | WSW | 9 |
| 23 | NE | 13 | ESE | 3 | NW | 7 | WNW | 14 |
| 24 | SE | 2 | SW | 1 | NW | 2 | | 0 |
| 25 | ESE | 1 | NE | 3 | SW | 5 | NW | 12 |
| 26 | ENE | 4 | NE | 2 | WNW | 14 | SW | 4 |
| 27 | S | 4 | WSW | 1 | ESE | 2 | WSW | 5 |
| 28 | E | 7 | WSW | 4 | E | 3 | SSW | 3 |
| 29 | E | 9 | WNW | 6 | WSW | 4 | SW | 4 |
| 30 | WNW | 10 | WSW | 5 | SW | 3 | W | 5 |
| 31 | | | ENE | 3 | E | 3 | | |
| Monthly Vector Resultant | NE | 33 | WNW | 38 | W | 106 | W | 72 |
| Daily Vector Mean | NE | 1.1 | WNW | 1.2 | W | 3.4 | W | 2.4 |

LAKE SUPERIOR - VECTOR LAND WIND VELOCITIES AT PORT ARTHUR, ONTARIO

TABLE 65

| Day of Month | Daily Mean Land Winds—1958 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | NNE | 7 | E | 5 | WSW | 7 | SE | 4 |
| 2 | ESE | 4 | ESE | 4 | WNW | 3 | SE | 2 |
| 3 | ENE | 6 | E | 8 | W | 5 | WNW | 6 |
| 4 | NE | 3 | E | 10 | E | 3 | W | 6 |
| 5 | NW | 12 | ENE | 12 | W | 10 | ENE | 2 |
| 6 | WSW | 8 | ESE | 3 | W | 14 | ENE | 4 |
| 7 | SW | 14 | NW | 1 | NW | 4 | NW | 4 |
| 8 | N | 2 | SSW | 5 | S | 6 | SW | 7 |
| 9 | NE | 6 | E | 7 | N | 1 | NW | 11 |
| 10 | NW | 5 | WNW | 5 | SE | 2 | NW | 8 |
| 11 | W | 14 | WSW | 3 | W | 1 | SW | 4 |
| 12 | W | 8 | E | 5 | WNW | 11 | N | 4 |
| 13 | NW | 12 | ENE | 6 | SSW | 5 | E | 5 |
| 14 | WNW | 7 | WSW | 9 | WNW | 5 | SSW | 4 |
| 15 | W | 9 | NW | 4 | WNW | 6 | WNW | 9 |
| 16 | W | 6 | W | 6 | W | 8 | ENE | 4 |
| 17 | SW | 5 | S | 8 | WSW | 4 | ENE | 5 |
| 18 | E | 5 | WNW | 15 | SW | 4 | S | 2 |
| 19 | SE | 3 | NW | 2 | ENE | 1 | SSW | 1 |
| 20 | WNW | 13 | ESE | 2 | WNW | 6 | SSE | 5 |
| 21 | W | 2 | WSW | 7 | WNW | 10 | W | 15 |
| 22 | SSW | 4 | S | 3 | WNW | 6 | SW | 7 |
| 23 | ENE | 6 | ENE | 6 | ENE | 4 | W | 1 |
| 24 | E | 8 | N | 3 | NW | 11 | SSW | 3 |
| 25 | NNW | 6 | SW | 4 | SW | 4 | W | 16 |
| 26 | NW | 23 | E | 3 | SW | 3 | W | 9 |
| 27 | WNW | 7 | NE | 3 | ESE | 4 | WNW | 6 |
| 28 | | 0 | W | 10 | NNW | 3 | WSW | 4 |
| 29 | NE | 8 | WNW | 8 | E | 7 | SE | 4 |
| 30 | ENE | 5 | W | 12 | E | 4 | WNW | 17 |
| 31 | | | SW | 6 | N | 14 | | |
| Monthly Vector Resultant | NW | 94 | WSW | 16 | W | 90 | W | 93 |
| Daily Vector Mean | NW | 3.2 | WSW | 0.5 | W | 2.9 | W | 3.1 |

TABLE 66

| Day of Month | Daily Mean Land Winds—1959 June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| 1 | SW | 5 | S | 3 | WSW | 3 | E | 6 |
| 2 | WSW | 8 | W | 2 | SW | 3 | SE | 3 |
| 3 | E | 7 | SSW | 5 | SE | 2 | SW | 4 |
| 4 | ENE | 5 | SSW | 8 | S | 5 | WSW | 6 |
| 5 | NW | 5 | WNW | 9 | E | 6 | SSE | 5 |
| 6 | ESE | 10 | W | 8 | NW | 3 | WSW | 11 |
| 7 | NNW | 1 | SSE | 4 | NE | 12 | WSW | 8 |
| 8 | NE | 3 | SW | 13 | E | 4 | E | 6 |
| 9 | W | 6 | W | 12 | SSW | 2 | WSW | 11 |
| 10 | ESE | 8 | WNW | 5 | NNW | 5 | WNW | 14 |
| 11 | NE | 7 | SW | 4 | SSE | 5 | WSW | 7 |
| 12 | WNW | 14 | W | 4 | NW | 12 | S | 2 |
| 13 | NW | 11 | E | 5 | SE | 4 | SW | 2 |
| 14 | E | 4 | E | 5 | WSW | 5 | NE | 10 |
| 15 | E | 9 | NE | 4 | SSW | 4 | N | 10 |
| 16 | ESE | 2 | SW | 6 | SE | 4 | WNW | 3 |
| 17 | ESE | 2 | N | 4 | WNW | 8 | W | 8 |
| 18 | ENE | 4 | WNW | 7 | E | 7 | SSW | 3 |
| 19 | NW | 7 | SE | 3 | SE | 6 | SSW | 3 |
| 20 | WNW | 6 | SW | 7 | E | 4 | ENE | 4 |
| 21 | WNW | 7 | ENE | 2 | ENE | 6 | NW | 2 |
| 22 | WNW | 7 | E | 7 | E | 10 | ENE | 10 |
| 23 | SW | 7 | WNW | 9 | E | 6 | W | 7 |
| 24 | E | 4 | WNW | 6 | W | 10 | WNW | 5 |
| 25 | E | 6 | SW | 7 | SSE | 2 | E | 7 |
| 26 | E | 5 | SSW | 6 | SW | 5 | SSE | 7 |
| 27 | E | 9 | E | 6 | E | 2 | SW | 12 |
| 28 | WNW | 5 | SSE | 5 | E | 4 | SW | 11 |
| 29 | WNW | 12 | SSW | 4 | E | 2 | WNW | 7 |
| 30 | SE | 4 | WNW | 10 | WNW | 3 | NNE | 3 |
| 31 | | | WNW | 14 | SSE | 2 | | |
| Monthly Vector Resultant | N | 25 | WSW | 89 | ESE | 26 | WSW | 62 |
| Daily Vector Mean | N | 0.8 | WSW | 2.9 | ESE | 0.8 | WSW | 2.1 |

# TABLE 67

## LAKE ERIE OVER-WATER-EFFECTIVE WIND VELOCITIES (LINEAR FUNCTION)

| Year | Resultant Wind[a] | | | On Axis (N 71°E) | | 3° Right of Axis | | 8° Right of Axis | | 11° Right of Axis | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | From | | mph | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared |
| 1950[b] | SSW | (214°) | 265 | 53 | 2900 | 52 | 2700 | 60 | 3600 | 63 | 4000 |
| 1951 | SW | (224°) | 518 | 91 | 8300 | 95 | 9000 | 102 | 10400 | 106 | 11200 |
| 1952 | SW | (214.5°) | 576 | 86 | 7400 | 90 | 8100 | 98 | 9600 | 104 | 10800 |
| 1953 | SW | (223°) | 505 | 187 | 17600 | 91 | 8300 | 98 | 9600 | 102 | 10400 |
| 1954 | SW | (235.5°) | 592 | 122 | 14900 | 126 | 15900 | 136 | 18500 | 141 | 19900 |
| 1955 | SW | (227°) | 304 | 56 | 3100 | 58 | 3400 | 62 | 3800 | 65 | 4200 |
| 1956 | SW | (227.5°) | 582 | 108 | 11700 | 112 | 12500 | 120 | 14400 | 126 | 15900 |
| 1957[b] | WSW | (238.5°) | 355 | 102 | 10400 | 106 | 11200 | 113 | 12800 | 116 | 13500 |
| 1958 | WSW | (240°) | 735 | 161 | 25900 | 167 | 27900 | 179 | 32000 | 184 | 33900 |
| 1959 | WSW | (237°) | 445 | 94 | 8800 | 97 | 9400 | 104 | 10800 | 108 | 11700 |

| Year | 13° Right of Axis | | 16° Right of Axis | | 18° Right of Axis | | 21° Right of Axis | | 23° Right of Axis | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared |
| 1950[b] | 65 | 4200 | 68 | 4600 | 70 | 4900 | 73 | 5300 | 74 | 5500 |
| 1951 | 109 | 11900 | 114 | 13000 | 116 | 13500 | 121 | 14600 | 124 | 15400 |
| 1952 | 106 | 11400 | 112 | 12500 | 114 | 13000 | 119 | 14100 | 122 | 14900 |
| 1953 | 105 | 11000 | 110 | 12100 | 112 | 12500 | 116 | 13500 | 119 | 14200 |
| 1954 | 144 | 20700 | 147 | 21600 | 114 | 20700 | 139 | 19300 | 136 | 18500 |
| 1955 | 67 | 4500 | 69 | 4800 | 71 | 5000 | 74 | 5500 | 75 | 5600 |
| 1956 | 129 | 16600 | 133 | 17700 | 136 | 18500 | 141 | 19900 | 144 | 20700 |
| 1957[b] | 118 | 13900 | 113 | 12800 | 111 | 12300 | 107 | 11500 | 104 | 10800 |
| 1958 | 180 | 32400 | 174 | 30300 | 169 | 28600 | 163 | 26600 | 159 | 25300 |
| 1959 | 110 | 12100 | 109 | 11900 | 106 | 11200 | 102 | 10400 | 100 | 10000 |

| Year | 28° Right of Axis | | 33° Right of Axis | | 38° Right of Axis | | 43° Right of Axis | |
|---|---|---|---|---|---|---|---|---|
| | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared | Eff. Wind | Eff. Wind Squared |
| 1950[b] | 80 | 6400 | 84 | 7100 | 87 | 7600 | 84 | 7100 |
| 1951 | 128 | 16400 | 121 | 14600 | 114 | 13000 | 107 | 11500 |
| 1952 | 130 | 16900 | 138 | 19000 | 142 | 20100 | 134 | 18000 |
| 1953 | 126 | 15900 | 119 | 14100 | 112 | 12500 | 105 | 11000 |
| 1954 | 128 | 16400 | 119 | 14100 | 111 | 12300 | 103 | 10600 |
| 1955 | 73 | 5300 | 68 | 4600 | 64 | 4100 | 60 | 3600 |
| 1956 | 138 | 19000 | 130 | 16900 | 122 | 14900 | 114 | 13000 |
| 1957[b] | 99 | 9800 | 91 | 8300 | 85 | 7200 | 78 | 6100 |
| 1958 | 149 | 22200 | 139 | 19300 | 129 | 16600 | 118 | 13900 |
| 1959 | 94 | 8800 | 88 | 7700 | 82 | 6700 | 75 | 5600 |

[a]Resultant wind is not an effective wind.
[b]Based on three months.
Note: Resultant wind velocity is in mph/summer season; effective wind is in mph/month.

## Barometric Pressure Effect

The magnitude and direction of the tilting of the water surface caused by the inequality of barometric pressure at opposite sides of the lake were calculated by means of J. F. Hayford's (1922, p. 11) formula for the barometric pressure effect. The barometric pressures used in the computations were obtained from the U. S. Weather Bureau's _Climatological Data, National Summary_ (1950-59) for American stations and from the Canadian Department of Transport, Air Services (Thomas, 1961, letter) for the Canadian stations.

Hayford's formula is as follows:

$$H_1 - H_2 = -(M_1 - M_2)(13.6)\left(\frac{1}{12}\right) = -(M_1 - M_2)(1.13)$$

where

$H_1 - H_2$ = barometric pressure effect, and

$H_1$ = elevation of water at point 1 (feet)

$H_2$ = elevation of water at point 2 (feet)

$M_1$ = barometric pressure at point 1 (inches of mercury)

$M_2$ = barometric pressure at point 2 (inches of mercury)

$$1.13 = \frac{13.6 \text{ (density of mercury)}}{1 \text{ (density of water)}} \times \frac{1}{12} \text{ (to convert M to feet)}$$

Example:—The summer season of 1950 with Buffalo as point 1 and Toledo as point 2 gives the following barometric pressure effect:

$$H_1 - H_2 = -(30.012 - 30.025)(1.13) = +0.015$$

In this case, the barometric pressure at Toledo was greater than that at

Buffalo by - 0.013 inches; the greater pressure at the western end of Lake Erie depressed the water at the western end and caused a rise at the eastern end (Buffalo) of 0.015 foot.

TABLE 68

LAKE ERIE BAROMETRIC PRESSURE EFFECT
BASED ON SUMMER SEASON MEAN BAROMETRIC
PRESSURES FOR BUFFALO MINUS TOLEDO (1950-59)

| Year | Barometric Pressure (Sea Level) | | | | | Barometric Pressure Effect, feet[a] |
|---|---|---|---|---|---|---|
| | Buffalo | | Toledo | | Difference, inch | |
| | mb | inch | mb | inch | | |
| 1950 | 1016.27 - | 30.012 | 1016.70 - | 30.025 | -0.013 | +0.015 |
| 1951 | 1016.15 - | 30.008 | 1015.92 - | 30.002 | +0.006 | -0.007 |
| 1952 | 1016.92 - | 30.032 | 1016.65 - | 30.024 | +0.008 | -0.009 |
| 1953 | 1017.90 - | 30.060 | 1017.95 - | 30.062 | -0.002 | +0.002 |
| 1954 | 1014.92 - | 29.973 | 1015.25 - | 29.982 | -0.009 | +0.010 |
| 1955 | 1016.65 - | 30.019 | 1016.25 - | 30.012 | +0.009 | -0.010 |
| 1956 | 1016.08 - | 30.006 | 1016.02 - | 30.005 | +0.001 | -0.001 |
| 1957 | 1016.30 - | 30.013 | 1016.40[b]- | 30.016 | -0.003 | +0.003 |
| 1958 | 1017.75 - | 30.056 | 1017.20 - | 30.039 | +0.017 | -0.019 |
| 1959 | 1014.82 - | 29.970 | 1015.30 - | 29.987 | -0.013 | +0.015 |
| 1950[c] | 1017.10 - | 30.037 | 1017.46 - | 30.047 | -0.010 | +0.011 |
| 1957[d] | 1015.80 - | 20.998 | 1016.00 - | 30.004 | -0.006 | +0.007 |

Notes: [a]+ = water higher at Buffalo; - = water higher at Toledo.
[b]Station pressure only is given for September 1957 in USWB Climatological Data, National Summary. Sea level pressure obtained by interpolation from sea level vs. station pressure graph.
[c]Based on three months (July, August, and September).
[d]Based on three months (June, July, and August).

TABLE 69

LAKE ONTARIO BAROMETRIC PRESSURE EFFECT
BASED ON SUMMER SEASON MEAN BAROMETRIC
PRESSURES FOR TRENTON MINUS TORONTO (1948-55)

| Year | Barometric Pressure (Sea Level) | | | | | Barometric Pressure Effect, feet[a] |
|---|---|---|---|---|---|---|
| | Trenton | | Toronto | | Difference, inch | |
| | mb | inch | mb | inch | | |
| 1948 | 1014.98 - | 29.974 | 1015.52 - | 29.990 | -0.016 | +0.018 |
| 1949 | 1015.78 - | 29.997 | 1016.08 - | 30.006 | -0.009 | +0.010 |
| 1950 | 1015.50 - | 29.989 | 1015.75 - | 29.981 | -0.008 | +0.009 |
| 1951 | 1014.88 - | 29.970 | 1014.80 - | 29.968 | +0.002 | -0.002 |
| 1952 | 1015.80 - | 29.998 | 1016.08 - | 30.006 | -0.008 | +0.009 |
| 1953 | 1015.87 - | 30.000 | 1016.20 - | 30.010 | -0.010 | +0.011 |
| 1954 | 1013.82 - | 29.940 | 1013.98 - | 29.944 | -0.004 | +0.004 |
| 1955 | 1015.85 - | 29.999 | 1015.88 - | 30.000 | -0.001 | +0.001 |

Note: [a] + = water surface higher at Kingston (Trenton).
- = water surface higher at Toronto.

# TABLE 70

## LAKE ERIE GAGE DIFFERENCES VS. EFFECTIVE WIND VELOCITY SQUARED (LINEAR FUNCTION)

| Gage[a] Difference | Direction of Effective Wind Relative to Toledo-Buffalo Axis | | | |
|---|---|---|---|---|
| | On Axis | Right of Axis | | |
| | Effective Velocity Squared ($V^2$) | Effective Velocity Squared ($V^2$) | | |
| | | From 3° | From 8° | From 11° |
| -0.19 | 2900 | 2700 | 3600 | 4000 |
| -0.04 | 8300 | 9000 | 10400 | 11200 |
| -0.07 | 7400 | 8100 | 9600 | 10800 |
| -0.10 | 7600 | 8300 | 9600 | 10400 |
| -0.03 | 14900 | 15900 | 18500 | 19900 |
| -0.21 | 3100 | 33400 | 3800 | 4200 |
| +0.01 | 11700 | 12500 | 14400 | 15900 |
| -0.06 | 10400 | 12200 | 12800 | 13500 |
| +0.05 | 25900 | 27900 | 32000 | 33900 |
| -0.14 | 8800 | 9400 | 10800 | 11700 |
| Correlation Coefficient | 0.84 | 0.84 | 0.85 | 0.85 |
| Regression Line | $1.06 \times 10^{-5} V^2 - 0.185$ | $0.981 \times 10^{-5} V^2 - 0.184$ | $0.863 \times 10^{-5} V^2 - 0.186$ | $0.826 \times 10^{-5} V^2 - 0.190$ |

| Gage[a] Difference | Direction of Effective Wind Relative to Toledo-Buffalo Axis | | | |
|---|---|---|---|---|
| | Right of Axis | | | |
| | Effective Velocity Squared ($V^2$) | | | |
| | From 13° | From 16° | From 18° | From 21° |
| -0.19 | 4200 | 4600 | 4900 | 5300 |
| -0.04 | 11900 | 13000 | 13500 | 14600 |
| -0.07 | 11400 | 12500 | 13000 | 14100 |
| -0.10 | 11000 | 12100 | 12500 | 13500 |
| -0.03 | 20700 | 21600 | 20700 | 19300 |
| -0.21 | 4500 | 4800 | 5000 | 5500 |
| +0.01 | 16600 | 17700 | 18500 | 19900 |
| -0.06 | 13900 | 12800 | 12300 | 11500 |
| +0.05 | 32400 | 30300 | 28600 | 26600 |
| -0.14 | 12100 | 11900 | 11200 | 10400 |
| Correlation Coefficient | 0.87 | 0.90 | 0.92 | 0.95 |
| Regression Line | $0.890 \times 10^{-5} V^2 - 0.201$ | $0.984 \times 10^{-5} V^2 - 0.217$ | $1.08 \times 10^{-5} V^2 - 0.152$ | $1.21 \times 10^{-5} V^2 - 0.248$ |

| Gage[a] Difference | Direction of Effective Wind Relative to Toledo-Buffalo Axis | | | |
|---|---|---|---|---|
| | Right of Axis | | | |
| | Effective Velocity Squared ($V^2$) | | | |
| | From 23° | From 28° | From 33° | From 38° |
| -0.19 | 5500 | 6400 | 7100 | 7600 |
| -0.04 | 15400 | 16400 | 14600 | 13000 |
| -0.07 | 14900 | 16900 | 19000 | 20100 |
| -0.10 | 14200 | 15900 | 14100 | 12500 |
| -0.03 | 18500 | 16400 | 14100 | 12300 |
| -0.21 | 5600 | 5300 | 4600 | 4100 |
| +0.01 | 20700 | 19000 | 16900 | 14900 |
| -0.06 | 10800 | 9800 | 8300 | 7200 |
| +0.05 | 25300 | 22200 | 19300 | 16600 |
| -0.14 | 10000 | 8800 | 7700 | 6700 |
| Correlation Coefficient | 0.98 | 0.94 | 0.84 | 0.72 |
| Regression Line | $1.25 \times 10^{-5} V^2 - 0.2543$ | $1.37 \times 10^{-5} V^2 - 0.193$ | $1.32 \times 10^{-5} V^2 - 0.166$ | $1.20 \times 10^{-5} V^2 - 0.216$ |

| Gage[a] Difference | Direction of Effective Wind Relative to Toledo-Buffalo Axis |
|---|---|
| | Effective Velocity Squared ($V^2$) |
| | From 43° Right of Axis |
| -0.19 | 7100 |
| -0.04 | 11500 |
| -0.07 | 18000 |
| -0.10 | 11000 |
| -0.03 | 10600 |
| -0.21 | 3600 |
| +0.01 | 13000 |
| -0.06 | 6100 |
| +0.05 | 13900 |
| -0.14 | 5600 |
| Correlation Coefficient | 0.68 |
| Regression Line | $1.29 \times 10^{-5} V^2 - 0.207$ |

[a]Gage differences are corrected for barometric pressure effect.
Note: Effective velocity is in mph/month; therefore $V^2$ is in $(\text{mph/month})^2$.

TABLE 71

LAKE ERIE GAGE DIFFERENCES
VS.
EFFECTIVE WIND VELOCITY SQUARED (COSINE FUNCTION)

| Year | Gage Difference | Direction of Effective Wind Relative to Toledo-Buffalo Axis | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | On Axis | | Right of Axis | | | | | | | | | |
| | | | | From 3° | | From 21° | | From 23° | | From 28° | | From 43° | |
| | | V | $V^2$ | V | $V^2$ | V | $V^2$ | V | $V^2$ | V | $V^2$ | V | $V^2$ |
| 1950 | -0.19 | 70.6 | 5000 | 73.2 | 5400 | 84.9 | 7200 | 85.6 | 7300 | 87.2 | 7600 | 87.8 | 7700 |
| 1951 | -0.04 | 115.4 | 13300 | 118.4 | 14000 | 128.7 | 16600 | 129.4 | 16700 | 129.4 | 16700 | 124.5 | 15500 |
| 1952 | -0.07 | 115.8 | 13400 | 120.1 | 14400 | 138.8 | 19300 | 140.0 | 19600 | 142.3 | 20300 | 143.1 | 20500 |
| 1953 | -0.10 | 111.4 | 12400 | 114.3 | 13100 | 125.3 | 15700 | 125.7 | 15800 | 126.2 | 15900 | 121.9 | 14900 |
| 1954 | -0.03 | 142.7 | 20400 | 144.5 | 20900 | 147.3 | 21700 | 146.7 | 21500 | 144.5 | 20900 | 131.3 | 17200 |
| 1955 | -0.21 | 69.5 | 4800 | 71.0 | 5000 | 75.9 | 5800 | 76.0 | 5800 | 75.8 | 5800 | 71.9 | 5200 |
| 1956 | +0.01 | 133.4 | 17800 | 136.3 | 18600 | 145.4 | 21100 | 145.5 | 21200 | 145.2 | 21000 | 137.2 | 18800 |
| 1957 | -0.06 | 115.5 | 13300 | 116.6 | 13600 | 122.5 | 13700 | 116.3 | 13500 | 114.1 | 13000 | 102.0 | 10400 |
| 1958 | +0.05 | 180.4 | 32510 | 181.9 | 33100 | 180.9 | 32700 | 179.6 | 32300 | 175.7 | 30800 | 155.8 | 24300 |
| 1959 | -0.14 | 107.9 | 11600 | 109.2 | 11900 | 110.4 | 12200 | 109.9 | 12100 | 107.9 | 11600 | 97.3 | 9500 |
| Correlation Coefficient | | 0.90 | | 0.91 | | 0.94 | | 0.93 | | 0.93 | | 0.89 | |

Notes: V = effective wind in mph/month.
$V^2$ = effective velocity squared.
Gage differences are corrected for barometric pressure effect.

Laidly 19150 Please return

# DISPOSITION FORM

SECURITY CLASSIFICATION (If any)

| FILE NO. | SUBJECT |
|---|---|
| | |

| TO | FROM | DATE | COMMENT NO. 1 |
|---|---|---|---|
| Dave: | | July 23 | |

The enclosed is my report to the Dist. Engineer on MacLean's doctoral thesis. My official connection with the Lake Survey expired June 30. I understand they are making a shorter version of this paper, which may be suitable for distribution. This will probably delete all references to MacLean or to Special Report No. 14, all recommendations for Lake Survey action, etc.

It is my feeling that as director of the Research Division, you should have the original, in order that you may see wherein I endorse or disagree with MacLean's statements. Probably you will receive the other later. Let's hope we all learn something by continued study!

Just returned from a delightful cruise on Georgian Bay. I shall never lose my enthusiasm for those wonderful lakes! Sincerely,

Bill

# ANALYSIS OF CURRENT PROCEDURES AND RESULTING RATES

# OF

# CRUSTAL MOVEMENT IN THE GREAT LAKES BASIN

An internal report to the D.E., U.S.L.S. not for publication

---

WILLIAM T. LAIDLY
CONSULTANT

U. S. LAKE SURVEY
DETROIT 26, MICHIGAN

JUNE 1963

ANALYSIS OF CURRENT PROCEDURES AND RESULTING RATES
OF
CRUSTAL MOVEMENT IN THE GREAT LAKES BASIN

TABLE OF CONTENTS

TEXT

# ANALYSIS OF CURRENT PROCEDURES AND RESULTING RATES

# OF

# CRUSTAL MOVEMENT IN THE GREAT LAKES BASIN

## I. INTRODUCTION

The present report may be considered as a part of a continuous study by the Lake Survey to learn more about crustal movement in the Great Lakes area. The report was initiated at this time, because of the preparation of a doctoral dissertation entitled "Postglacial Uplift in the Great Lakes Region," submitted to the University of Michigan by William F. MacLean of the Geology Department, and published in December 1961, as Special Report No. 14, Great Lakes Research Division, Institute of Science and Technology. In this publication MacLean disagrees strongly with present methods of obtaining crustal movement rates and with the magnitude of those rates.

Special Report No. 14 is a very comprehensive work of research in several related scientific fields, and the author is commended on its accomplishment. In general the present paper will concern itself with basic questions posed by MacLean. It is not its purpose to refute or confirm each statement of his work, but only those having definite bearing on the work of the Lake Survey or the Vertical Control Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

The recommendations herein have been made after consulting many geologic and engineering references. Some new problems are brought up by MacLean's report, and some old ones, for which solution has not been found, are revived. Several aspects of crustal movement still cannot be explained with complete confidence.

## II. GENERAL

### Absolute and Relative Rates

From the descriptions in Special Report No. 14, absolute rates of crustal movement may be defined as being those referred to mean sea level, which has been corrected for meteorological effects and eustatic rise. The report implies that the rates which have been determined for the Great Lakes-St. Lawrence River basin are, or should be, in this category. They are in fact relative rates of movement with respect to other localities on the lakes and to uncorrected sea level at New York City. The Lake Survey and the Vertical Control Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data are not primarily concerned with the absolute rate of movement at a particular point on a lake or with its relation to sea level, but with its rate of movement relative to the lake's outlet for use in hydraulic and dredging activities.

Without regard to sea level, an approximate rate of movement per mile may be derived from two relative rates on the same lake. This, however, assumes a uniform rate of movement, which cannot yet be accepted. There are too many indications from water gage records of non-uniform movement

to be explained wholly by errors or by meteorological effects on the gages. For this reason it is believed that any pair of gages on the same lake may be used for comparison of crustal movement rates, without regard to the alleged hinge line or area of horizontality. This concept does not discard the theory of a gradual postglacial uplift northeastward, because this pattern has been established by all methods of observation.

## Eustatic Change in Mean Sea Level

There seems to be no doubt that mean sea level itself is rising, due presumably to the increased volume of sea water caused by slow melting of polar ice caps resulting from the long range increase in average temperatures. Gutenberg (1941) published a study using 71 water gages located all over the world, and arrived at a rise of about 10 cm per century. This rate has been endorsed by Rossiter (1962). It is, of course, only a good estimate subject to further study with more data.

Moore (1948) did not recognize any eustatic rise in mean sea level. The Lake Survey, having based its reference on the tide gage at New York, has not subsequently taken the rise into account, because there would be no change in the relative rates of movement in the lakes sytem. The Vertical Control Subcommittee has not yet computed a relative rate between Lake Ontario and its key gage at Father Point, Quebec, from recent and past precise level lines. Should the subcommittee decide that rates of movement computed for points on the lakes should be referred to mean sea level, it will be necessary to add 0.33 foot (Gutenberg's 10 cm) algebraically

to all rates in the basin. Such a decision is considered unlikely, as the Father Point gage is believed to be above sea level an undetermined amount, probably in the order of 0.2 foot, and the practical value of the relative rates would not be enhanced.

### Concept of Rates of Movement

The Lake Survey has never considered its rates of crustal movement as anything more than approximations of the magnitude of this physical phenomenon. Time periods are relatively short and the rates are of such small magnitude that many anomalies are present. Many short period rate determinations by the Vertical Control Subcommittee are of little value because of the scarcity of data; however, it is believed that the rates as a whole are the best possible determinations of modern rates with the use of existing data, and are valuable within the concept of accuracy expressed in this paragraph.

## III. GEOLOGICAL ASPECTS

### Present Geological Theories

Most modern geologists are agreed that crustal movement in the Great Lakes region is the result of an uplifting of the earth's crust in a general northeasterly direction following the last recession of the Wisconsin glaciation. Based on field observations they postulate a hinge line passing through the extreme western end of Lake Superior from about

Two Harbors and Ashland, continuing roughly through Escanaba, Traverse City, Harrisville and Kincardine, and projected without field evidence through the western end of Lake Ontario in the vicinity of Toronto and Olcott. South of this line in the so-called area of horizontality, no crustal movement is presumed to have taken place since the time of the Nipissing Great Lakes, and north of the line the land is apparently continuing to rise at a rate which increases northeastward. All of these concepts are based upon the discovery and identification of old lake beaches formed by the predecessors of the present Great Lakes, and upon the determination of their age and height.

The initial comprehensive work on the geology of this region was done by Leverett and Taylor (1915). They were preceded and followed by many capable investigators working in localized areas. The most recent complete work is that of Hough (1958), who in effect brought Leverett and Taylor up-to-date as a result of subsequent field work and new interpretations. All of these works supply convincing evidence to support the current geologic theories, however, there are dissenting opinions regarding the absence of crustal movement south of the Nipissing isobase or hinge line. Evidence gathered by the Lake Survey puts it in this minority group. It must be remembered that no theory in the geophysical sciences is sacred and each is subject to revision because of new evidence or reinterpretation of the old; for example, Hough is already revising his 1958 treatment of Lake Ontario, because of new discoveries by investigators in that area.

## Measurement of Heights of Old Beaches

No extensive determinations of old beach elevations have been made since Leverett and Taylor. These early measurements as well as most of the later ones were made with altimeters or hand levels, and at times elevations were taken from contour maps. These crude methods coupled with the obvious difficulty of placing the leveling rod or other type staff, if any, on the irregular crest of the old beach throw considerable doubt on the results obtained. Stanley (1935, p. 448) stated:

> "...... in the final act of measuring the beach, variations of a foot or so are always to be found in its gravelly, grassed-over surface."

A further cause for error was suggested by Stanley on the same page:

> "It is recognized by students of shore forms that gravel ridges may be built at varying heights above or below the water level."

Hough (p. 134) declared:

> "The elevation of the crest of a depositional beach ridge varies from place to place, depending on the height of storm waves which reach the shore and on the amount and size of debris available for beach construction. Constructional forms such as ridges and bars generally have crest elevations which are higher than wave-cut terraces formed elsewhere in the same lake."

MacLean (1961, p. 33) expressed his opinion on the subject as follows:

> "The inaccuracies inherent in the instruments and methods coupled with the difficulties of determining the elevation of the former water surface ---- i.e., of correlating wave-cut features with wave-built features of lakes whose surfaces varied several feet in elevation from year to year ---- result in elevations which are probably accurate from ±5 to ±10 feet."

Taylor (Leverett & Taylor 1915, p. 429) has this to say:

> "In his early work on the beaches in Ontario, Spencer used the spirit level. Since that time, however, most investigators, including Mr. Leverett and the writer, have used only the aneroid barometer and the hand level, and though results obtained by these last two methods are serviceable for general purposes they are not accurate enough to settle the relations of the planes of the different beaches or to determine the variations in the rate of inclination of those planes."

MacLean (p. 39) is obviously correct in his statement that for rates of past uplift, the measurement of differences in elevation of old beaches, based on time periods which may reach 13,000 years, is satisfactory for accurate results. Gutenberg (1942, p. 148) agreed when he said:

> "Of course, the tide gauge data furnish only the present rate of uplift; the average rate during the past centuries can be found only from field data."

In view of the foregoing discussion of measurement inaccuracies and the difficulties present even with accurate methods and good instruments, it appears that field measurements of old beach heights are not suitable for determining modern rates of movement, and produce questionable results even as far back as the comparatively recent Nipissing stage. For the period since that stage MacLean (p. 38, table 1) computes a slope of 55 feet/100 miles from Walkerton, Ontario, to Field, Ontario, in the

Lake Huron basin, and a slope of 49 feet/100 miles from Wakefield, Michigan, to about 4 miles north of St. Ignace Island, Ontario, in the Lake Superior basin. If we assume a measurement error of 5 feet in opposite directions at each station (the minimum error suggested by MacLean), the resulting error in rates would be about 18 and 21 per cent, respectively. The rates have not been constant since the Nipissing Great Lakes. Had they been so, these rates would have been about 1.70 feet/100 miles/100 years and 1.20 feet/100 miles/100 years respectively. Logically, the modern rates by gage comparisons for comparable locations are much smaller, being approximately .50 foot/100 miles/100 years in each case.

## Alleged Area of Horizontality

Geologists assume an area of horizontality in the southern portion of the Great Lakes basin, south of a "hinge line" as described earlier in this section. In this area crustal movement is supposed to have ceased some 3000 years ago. As previously stated in Section II, a uniform rate of movement cannot yet be accepted, nor can the complete absence of movement south of the ill-defined hinge line, even in the Lake Erie basin. Evidence will be presented subsequently to demonstrate the probability of a non-uniform movement with a basin-wide pattern of uplift northeastward. There is considerable support for the idea of a present and continuing movement in the area of horizontality, both from the study of gage records and from geological evidence. Freeman (1926, p. 149) states that:

> "Whatever the cause, continuous progressive tilting upward toward the north at the rate of about half a foot per 100 miles per century in the southern part of the Lake region, with indications of double this rate over some parts of the Lake system, is proved beyond all doubt, by the comparisons of simultaneous water heights at some 20 pairs of water gage stations ------".

Stanely (Greenman & Stanley 1940, p. 199) had this to say:

> "Forty years ago G. K. Gilbert concluded from a study of comparative lake gauge readings that postglacial tilting of the Great Lakes region is still proceeding (subsequent readings have verified this)."

Hough (p. 268) in describing the transition from the Algoma (post Nipissing) stage to the present Great Lakes makes this statement:

> "---the surface of Lake Erie has been raised by uplift of its outlet at the northeastern corner of the basin."

and recently (1963, p. 105) confirmed his view as follows:

> "Lakes Ontario, Erie, and Superior are still rising and encroaching on their southern and southwestern shores, ---"

MacLean (p. 30) makes this point in referring to the zone of horizontality:

> "The degree of restoration is probably not complete due to the thick overburden of glacial drift which covers the glaciated region south of the Canadian Shield."

These opinions cast considerable doubt on the theory of an area in which no postglacial uplift is occurring. Certainly it is an area in which some sort of movement is present.

## Field Evidence of Movement in the Lake Erie Basin

The studies reported by Moseley (1904) are especially significant in this respect. In the Sandusky Bay area he found much to support the idea of a recent uplifting of the outlet of Lake Erie at its eastern end, resulting in a gradual rise of the water in the bay. Some of the evidence was noted personally and some from persons who recalled the conditions of an earlier time. All of the cited changes may be dated within the 18th and 19th centuries. There are numerous cases of submerged stumps and trees of kinds that will grow only on dry land, of dead trees killed by high water, of loss of area on the mainland and islands to an extent that cannot be explained by storms or seasonal fluctuations, and of the formation of much marsh land, which can be due to higher water alone and not to erosion. One resident claimed in 1904 that there were 2-1/2 feet of water on 200 acres of his land which had been dry at his coming there in 1836. Moseley recounted instances of channels becoming deeper and wider. It was possible to walk to Eagle Island in the west end of the bay in the early 19th century, and Squaw Island in the same area was connected to the mainland. The main channel at Cedar Point was so narrow that Indians swam their ponies across it, and settlers on the Marblehead Peninsula drove their cattle to market this way prior to 1830. Human bones have been found in several graves below water level in the Squaw Island region. Moseley himself found two large cottonwood trees several yards apart in this vicinity, whose roots had become loosened by high water, causing them to fall. Imbedded in the earth clinging to the upturned roots of

these trees he found parts of human skeletons, together with artifacts of the period.

Taylor (1915) discounted Moseley's theory of the cause of flooding in western Lake Erie due to the rising of land to the northeast by asserting that the phenomenon was due to a rise in level of Lake Erie caused by the abandonment of the Mattawan outlet in the Lake Huron basin, allowing a large discharge through the Port Huron outlet rather than through the Ottawa River. Because of the recentness of events found in Moseley's studies, Taylor's assumption does not seem valid. It can be shown that Lake Erie level in the past 100 years has not risen due to increased supplies and/or outlet regimen changes.

Moseley submitted much further evidence of recent crustal movement with his investigations by borings in drowned stream beds in Sandusky Bay, but perhaps the strongest argument lies in his study of the lake-formed ridges on Cedar Point. Moseley took five well defined, roughly parallel ridges and determined their approximate ages by counting rings in cedar stumps on them and correlating this figure with the known time of cutting and other physical data on the ridge. The ages of the ridges ranged from 45 to 475 years, the youngest and highest being on the Lake Erie side and the oldest and lowest on the Sandusky Bay side. He then dug into the ridges in about 150 places to determine the highest level of aqueous deposits in each ridge. Then by comparison of the aqueous deposit heights and the ages of the four older ridges with these same values in the youngest ridge, four determinations of the rate of movement were obtained, which averaged 2.22 feet per century over a small range of values. This rate may be considered high, but it is

good evidence of recent crustal movement in a zone where movement is supposed to have stopped centuries ago.

### Type of Movement

The foregoing studies and opinions give credence to the existence of crustal movement in the alleged area of horizontality, as do present day studies of gage records, which will be discussed in a subsequent section. The type of movement, even with the elimination of possible errors and known inadequacies of some gage records, is believed to be a non-uniform movement with a basin-wide pattern of northeasterly uplift. Although expressing doubt that any measurable movement of uplift had occurred within the last 100 or 150 years, Taylor (p. 468) had this to say:

> "The author is inclined to the belief that the movements of uplift are spasmodic in character and occur rather suddenly at intervals separated by long periods of rest, during which movements do not occur."

Further, Taylor did not rule out the possibility that movement was due to other tectonic causes, such as crustal creep or hydrostatic relief. In regard to the latter he stated (p. 509):

> "On account of its slowness, however, the hydrostatic relief may be still in progress and not yet fully satisfied."

## IV. DETERMINATION OF CRUSTAL MOVEMENT RATES BY WATER LEVEL COMPARISONS

### Present Concepts

In order to strengthen the case for existence of movement in the "area of horizontality," it is necessary to examine comparisons of elevations of

water level gages in that area over extended periods of from 50 to 100 years. Recorded elevation differences between two gages on the same lake, plotted against long periods of elapsed time, show in most instances a pronounced line slope, which cannot logically be explained by meteorological effects or gage errors. It must be movement of the land at one gage site in relation to that at the other.

Accepting the foregoing premise and the argument of Section III that geological field measurements are unsuitable for determining modern rates, it follows that the only practical way to obtain rates of relative movement on the same lake is by water level comparisons. Certain errors, as discussed in Special Report No. 14, are possible with this method and must be examined further.

## Gage Location Effects

Improper location of water gages can be a major source of error in the recording of true lake level, but the ability or inability to do so has no effect on the determination of rates of crustal movement by water level comparisons over long periods. The only effect on crustal movement rates would be caused by a permanent change in the physical environment of a gage located in a constricted area such as an enclosed harbor or mouth of an inflow river, due to dredging, filling or other major construction, or by a progressive change in regimen of the adjacent river. These changes affect the capacity of the water body near the gage and thus affect its readings. Gages located in mouths of inflow rivers are subject to

variations with respect to lake level, due to seasonal changes in river flow, but these variations have no effect on long period crustal movement rates because they are not progressive; moreover, the seasonal changes in flow occur in months not normally used for water level transfers.

Several Lake Survey gages are in constricted locations as described in the previous paragraph and should be moved to open lake positions as soon as practicable in the interest of better water levels for all concerned. This improvement is in progress at the present time as funds become available; for example, the gages at Rochester, Cleveland and Monroe have recently been removed to more favorable locations. Comparatively new sites, such as Lakeport and Point Iroquois, have been established to give open lake recordings. There is little that can be done to improve the general location of gages in many converging shore areas such as those at Duluth, Green Bay, Essexville, Toledo and Buffalo. It must be remembered that the primary responsibility of the Lake Survey in water level gaging is to record elevations for the benefit of navigation and other marine interests, and that local riparian owners and marine contractors want maximum, minimum and average levels at a particular locality. Depending upon the conditions at each place, however, movement of a gage site from inside a river or breakwall to open water, such as the change of the Milwaukee gage some years ago from the river to the outer light, should be seriously considered. The Calumet gage, located inside the harbor and about 1/2 mile up the Calumet River, is an example of a gage which should be moved outside for improved service to a large industrial region.

## Instrument Errors

There are a number of errors inherent in water level recording equipment, which are explained by Stevens in his Hydrographic Data Book (undated, pp. 20-40) and referred to by MacLean in Special Report No. 14. These errors are generally negligible in modern recording gages used by the Lake Survey, and of little consequence in all automatic gages used since the beginning of this century. The reasons for this will be explained in connection with each type of error.

Float lag is the failure of the float and its assembly to follow instantly the rise or fall in the water surface, such as in the case of two meshed gears. If there is play between the gear teeth, the follower will lag behind the driver the amount of this play. Float lag error is negligible when a large float, a small counterweight and a light flexible line is used and the instrument is kept in good condition. It is minimized further when the gage is not used for direct measurement, but in conjunction with a reference gage, as has always been done by the Lake Survey. A graduated tape line is used on the recording gage, and the value of the index pointer is determined, but this is used only in the rare instance when the reference gage is inoperative, or as a check on the water surface elevation at daily inspection times. Reference gages are not subject to this error.

Line shift is the error caused by a change of a part of the float line or tape from one side of the float pulley to the other, due to a change in water stage. This shifting in weight of line changes the depth of floatation of the float, causing a small error depending upon the amount of stage change. In most Lake Survey gages the range of level is too small to

generate appreciable error. In those gages with relatively large range, such as Buffalo and Toledo, the error can be made negligible by use of the largest float possible consistent with instrument and installation design.

Error due to submergence of counterweight is not at all applicable in most cases due to small range of stage and ample height of the gage instrument above water. It is of negligible amount in those cases of actual submergence, due to the use of a small 6 ounce counterweight.

Although the maximum amount of error among the foregoing (float lag) is in the order of .01 foot, there is the possibility that in isolated instances the errors may be cumulative. Since all are inversely proportional to the square of the diameter of the float, it is recommended that where the size of the well and other conditions permit, 10 inch floats be installed at all gages which do not have them. This is possible in over 50 per cent of the gages. Since the diameter of the float pulley of the Stevens A-35 gage is 6 inches, the 10 inch float is the largest that may be used without interference with the counterweight unless additional frictional members are introduced, which action would probably negate the primary purpose.

Errors due to humidity effects on chart paper may amount to as much as 2 per cent under extreme conditions of excessive humidity, however, such conditions do not occur in the Great Lakes region except for very short periods. Although under ordinary conditions this error is negligible, there are no means of knowing whether change in the paper has occurred when it is ready to be scaled in the office. It is believed that the two base line

markers at a fixed distance apart as recommended by Stevens (p. 33) should be used to detect the presence of this error. The standard time markers and reversal indicators may be used for this purpose, and the latter are already on the instruments.

Gage instruments of the last half of the 19th century leave much to be desired in design and operation. There were only a few self-registering gages at the inception of continuous records in 1859, the remainder consisting of boards, staffs and floats of various types which were read tri-daily, daily or intermittently; however, all are considered good enough to indicate the trend of crustal movement. A single reading taken at noon each day is quite useful in producing a monthly mean, and tests have shown that the mean of tri-daily readings taken at 7 a.m., 12 p.m. and 5 p.m. is almost as accurate as the mean of 24 hourly readings. Several recent random comparisons of monthly means in Lake Erie between values derived from the normal hourly scalings and those derived from scalings at the foregoing tri-daily hours show an average difference of .002 foot.

## Operator Errors

One cannot doubt the possibility of human error in the operation of water gages, because they have been known to occur. It is significant, however, that many precautionary measures and checks have in nearly all cases prevented errors, and in those instances which escaped notice, the effect has been minimized in the monthly mean averages. The several examples of erratic water gage operation and care quoted by MacLean from

Lake Survey reports serve only to emphasize the vigilance of responsible personnel in detecting such errors by examination of records and comparison with other gages. The care of gages in the early years of this century, while not up to present day standards, is believed to have been adequate. Early tri-daily float gage readings are likewise considered to be accurate enough for determination of crustal movement rates, which were designated earlier in Section II as approximations. There was careful instruction to observers, thorough inspection of floats and wells and meticulous checking of staff graduations. In appropriate instances special platforms were built on the sides of docks to assure that all readings would be made at eye level.

The change of significant operator errors today is considered extremely remote. Competent operators are given careful verbal instructions, and written instructions for making daily inspections are posted in gage houses. Supervisory inspections and levels to bench marks are done twice yearly, and bench mark stability is assured by leveling triennially to all marks in the vicinity. Readings and scalings are made to the nearest .01 foot, and mean values are independently checked. The ultimate use of electronic equipment for record processing, as now used by the Canadian Hydrographic Service, will further reduce the probability of error.

## Meteorological Effects

The potential errors in water levels due to meteorological effects have been demonstrated by several investigators in recent years, and their

existence cannot be doubted. Unquestionably, they are the most significant errors in water level transfers. They do not, however, have any effect on the determination of crustal movement rates over long periods. The differences shown by two gages due to wind set-up for each month or year are random values, which do not change progressively with time, because wind force itself does not so change.

In his work on mean sea level Gutenberg (1941, p. 724) considered that the differences in water levels at various gage sites were due chiefly to meteorological effects, and that the effect was considerably lessened by using gages having long periods of record. He states:

> "To reduce the effects under discussion on the values of the calculated sea levels, the author has given greater weight to a few selected stations where a long series of observations is available, so that the undesirable variations are of small influence; ----"

In regard to similar problems on the lakes he says (p. 728):

> "Data on lake levels are to be treated similarly. In this case the effects of wind and air pressure are usually smaller, ----"

and regarding irregularities due to ice conditions at Quebec (p. 746) he states:

> "Like the effects of meteorological conditions, these effects probably average out by taking differences between series of years."

MacLean agrees with Gutenberg about the lessening or elimination of meteórological effects on the ocean when he says (p. 57):

> "If mean sea level is derived from 19 years of tidal observations, the meteorological effects as well as the astronomical tides should be eliminated."

but disagrees with the statement that wind set-up is usually smaller on the lakes, especially on Lake Erie, because of its shallowness, long narrow shape and pointed ends. MacLean is probably correct in this matter. It also appears reasonable that, in general, long period gage records tend to minimize meteorological effects on water levels.

Barometric pressure gradients on the Great Lakes are not large, consequently, the resulting effect on lake levels is of little importance. The difference in effect between two gage sites may be plus or minus and tend to be compensatory, as illustrated in the Buffalo-Toledo example by MacLean (p. 179, table 6), in which the positive and negative quantities exactly balance for the years 1950-59. The barometric pressure effect need not be considered unless correction for wind set-up also is calculated.

Wind set-up may account for nearly the total lake level difference between pairs of gages, as illustrated by MacLean in his "hindcast" of level differences between Toledo and Buffalo on Lake Erie in 1950-59, however, this comparison does not prove that gage differences measure only average net set-up. Crustal movement, if present, is also included, however, a determination from this 10 year period would be worthless. Short term gage records often show abnormal rates. Neither can it be deduced from MacLean's example that over extended periods the phenomenon called crustal movement by the Lake Survey consists entirely of average net wind set-up. The high correlation coefficients show a strong relationship

between winds and changes in gage differences, and reflect the fact that over a period of only 10 years the changes in differences are determined more by wind set-up than by possible crustal movement. The differences could have any values, and as long as the changes in differences are the same, the same degree of correlation would be obtained.

Since the crustal movement rate between Toledo and Buffalo as determined by the Coordinating Committee is only 0.12 foot, there is little or no effect of crustal movement in the relationship shown in MacLean's hindcast graph (p. 146, fig. 9). His argument would have force only if the same results were obtained over a period long enough so that a correlation could be shown between a progressive change in the differences and a similar progressive change in meteorological conditions, if any.

There are many plots of gage differences covering periods of 50 to 100 years that show a pronounced slope in the best fitting line drawn through them. This slope can only be explained by relative movement of the land at the gage sites. The normal line in such a plot demonstrating only average net wind set-up between two points would be a horizontal line at a fixed distance above or below the zero axis equal to the amount of the average net set-up. To obtain a sloping line the wind would have to increase or decrease progressively over a long period, and this is not physically true. The tendency of plotted points to veer from the best-fitting line or to assume a new alignment for a period of say 10 or 20 years can be attributed principally to either the spasmodic change of rate previously suggested, or to a change in meteorological effects. Moore (1948, p. 706) recognized both these possibilities when he said:

"The scattering of the points is believed to be due to varying wind and barometric conditions. The comparison between Milwaukee and Harbor Beach (Fig. 2) shows two possible interpretations of the data. It is not impossible that Milwaukee is on a block which is undergoing periodic subsidence with longer periods of stability."

There are, of course, other causes for shifting away from the alignment pattern, such as changes in gage zeros or local changes in bench marks. Errors due to these causes are considered practically non-existent in present day records due to current procedures in inspections and leveling. While their occurrence in the early days of gaging may have been more frequent, it is believed that few of them are perpetuated in the records. Water levels have been corrected as soon as errors have been found, and the several examinations at the time of establishing new datum planes have resulted in additional screening and correction. Water level transfers have usually been made from two or more gages. In many gage locations wind set-up, if any, is negligible, and as previously explained, has no effect on the determination of crustal movement rates over long periods.

The basic idea of past water level transfers for use in carrying precise elevations has been attacked in Special Report No. 14, because the surfaces of the lakes are not level even in the summer months. This is true, particularly in Lakes Erie and Ontario, where the magnitude of the set-up may be significant. The water level transfer, however, is the most accurate method of carrying elevations in the lakes region. Its error is less than the allowable error in first-order leveling. It has repeatedly closed loops in connection with land lines with satisfactory results, some of which are indicated in these recent examples. In 1960 the 43 mile land line between

Cheboygan and Petoskey, Michigan, and the 65 mile water level transfer between these points checked by .06 foot. In 1954 the 148 mile land line between Goderich and Collingwood, Ontario, and the 200 mile water level transfer agreed exactly. The IGLD elevation at Goderich, established from Kingston by a 550 mile combination of water level transfers through Lakes Ontario and Erie and first-order levels along the Welland Canal and the Detroit-St. Clair Rivers, checked that obtained by 318 miles of first-order leveling direct from Kingston by 0.28 foot.

It is reiterated that the Lake Survey has never considered its published crustal movement rates as anything more than approximations of the true relative values. No action is necessary with regard to correction for meteorological effects, because there are no effects over long periods. For the sake of more accurate elevations per se. It would not be practical to attempt correction on a system-wide basis due to lack of meteorological data, nor is it believed practical from an economic viewpoint to provide the means for so doing in the future. It is recommended, however, that in the interest of research, corrections for wind set-up and barometric pressure effects be made only on Lakes Ontario and Erie in connection with the principal water level transfers for the next revision of International Great Lakes Datum. Such action may require minor changes in the precise level and water level transfer patterns, and the establishment of one or two stations to gather wind data, but the results obtained should be valuable, since wind set-up is significant on Lakes Ontario and Erie.

## V. DETERMINATION OF CRUSTAL MOVEMENT RATES BY PRECISE LEVELING

### Present Concepts

First-order leveling is important in determining the trend in modern rates of earth movement, and is the only acceptable method in areas where lake surfaces are not available. It permits the relating of one lake to another and the whole system to a common reference point. Because of the relatively short periods of years between runs, the allowable error in precise leveling work between two points is usually greater than the crustal movement between them, however, the level error is compensatory and the trend is evident. This has been demonstrated many times by plotting the differences in elevation of bench marks of identical lines run a significant number of years apart using instrumental differences in order to avoid the effects of loop adjustment and the orthometric correction. Local instability of marks and the presence of earth faults are readily detected. The Lake Survey reduces the amount of probable error by requiring closures of 3 millimeters times the square root of the distance in kilometers, rather than the required 4 mm $\sqrt{K}$ used in first-order levels.

MacLean (pp. 85-92) compares Great Lakes leveling with certain level work in Finland and implies the superiority of the latter in determining crustal movement rates. This superiority is undoubtedly true, because of relatively short lines, many closed loops and frequent connections to tide gages. So far as operations are concerned, the foreign work is not of higher quality. Methods, equipment and care of marks in Canada and the United States are just as good. The difference lies in the fact that the

control system for the lakes must be extended inland about 1750 miles from the ocean to Duluth without benefit of connections to tide gages at both ends of the line or in between. The present lines are strengthened by frequent loop closures across the several waterways that separate Canada and the United States. The former basic elevation at Oswego (1903 and 1935 datums) was obtained from Rensselaer by means of a closed loop consisting of land levels through the Mohawk and Oswego River valleys, and land levels and water level transfers via the Hudson River, Lake Champlain, International Boundary, St. Lawrence River and Lake Ontario. This loop closed with a discrepancy of .02 foot.

## Validity of Vertical Control on the Lakes

Special Report No. 14 does not question the validity of the vertical control system on the Great Lakes specifically in connection with hydraulics and water levels, but for its use to determine crustal movement rates. Some of the references and quotations, however, may give the impression that the control system is of little value. The system is and has been as strong as it could be made with available instrumentation and accepted methods. From the beginning of the present century until the inception of IGLD (1955), it has been connected to the Coast and Geodetic Survey network under their 1903 adjustment at key points on the lakes. In this adjustment water level transfers were given top weight with their best land lines. The present system using dynamic values is considered equally strong, and at all times the land and water network of the lakes system has been accurate enough to allow

approximations of relative crustal movement rates to be made. This statement cannot be made of rates between Oswego and Mean Sea Level at New York, because the Lake Survey current rates at Oswego is apparently grossly in error as a result of the previous computation of the movement of the land at Rensselaer. Since the connection to the sea is no longer at New York, a study has not been made to find the best rate at Oswego relative to sea level. This will be determined by comparison of level lines from Father Point to Kingston, and the result compared with a new determination from New York.

In his tabulation for the 1950-59 Lake Erie hindcast MacLean (p. 179, table 6) shows the calculated and observed gage differences between Buffalo and Toledo generally as minus quantities, which is in accordance with the actual recordings, Toledo showing generally higher than Buffalo for the period. With a wind set-up in the direction of Buffalo this may seem paradoxical, however, it is explained by MacLean (1962) as being because the Toledo gage zero is too high as a result of the water level transfers establishing datum at that point. If an effective wind velocity of zero is substituted in his wind slope equation, the regression line cuts the y-axis at -0.25 foot, which suggests that the elevation of the Toledo gage is too high with respect to Buffalo by this amount. Whether this is true or not cannot be determined at this time. It is interesting to note that if the known 1935 datum discrepancy of 0.38 foot between Lake Ontario and Erie is taken away, the resulting elevation at Toledo obtained by water level transfer and land levels is 0.11 foot lower than its elevation on 1903 datum, which was determined by land levels only; and to note that

the aforementioned IGLD elevation at Goderich, obtained through Lakes Ontario and Erie, is 0.28 foot lower than that obtained solely by land lines from Kingston. In other words, these two examples indicate that Toledo could be too low.

## The Father Point Gage

Special Report No. 14 characterizes as "dubious" the selection of the Father Point gage as the initial reference point for IGLD because it is in an area still subjectto uplift, it is located in the estuary of the St. Lawrence River, therefore subject to greater meteorological effects, and it is separated from all of the Great Lakes region by an ancient fault line (Logan's Line). The Coordinating Committee in its report on establishment of IGLD (1961, p. 6) states its reasons for selection of this site, the principal one being that this is the location of a long-record gage at the outlet of the Great Lakes system. The selection was not only logical, but almost mandatory. The nearest acceptable gage would be at Halifax, several hundred miles to the southeast on the Atlantic coast, requiring a large amount of additional leveling. Meteorological effects at the location of the Father Point gage on the 25 mile wide estuary are not considered to be significant in view of the present concept of the order of accuracy in crustal movement rates.

All gage sites on the Atlantic seaboard are subject to movement at rates of varying magnitudes, with Father Point being the least of all (rising about .17 foot/century) according to tide gage records uncorrected

for eustatic change. It is worthy of note also that Canadian Geodetic Datum is based on mean sea level computed from gage readings prior to 1910 at Yarmouth, Halifax, Father Point, Vancouver and Prince Rupert, and that the value of BM "R" at Father Point on this datum is 17.192 feet. The new value of BM "R" for IGLD about 50 years later is 17.234 feet. The foregoing seems to indicate that movement is still going on at Father Point, but that the magnitude of change is small.

## VI. SUMMARY

1. Crustal movement rates are considered to be only approximations of the magnitude of this phenomenon. They express not the absolute rate of movement at a particular point, but the relative rate with respect to other points in the system. They are generally the best possible determinations with existing data, and are valuable within the foregoing concept of accuracy.

2. Field evidence from water level gaging, geologic studies and precise leveling points strongly toward the existence of a non-uniform movement with a basin-wide pattern of uplift northeastward.

3. Determination of crustal movement rates from field measurement of old beach heights is the only method that can be used for the period before water level gaging began. It is not as accurate as the method of water level comparisons for the modern period since 1860.

4. Movement is still going on in the alleged area of horizontality in the manner stated for the remainder of the basin. This view is supported

by geologic evidence and by water level comparisons, in which the best fitting line through gage differences shows a definite slope over long periods. Location of gages with respect to a "hinge line" has no effect on the relative rates of movement.

5. Comparison of water level differences is the only satisfactory method for obtaining crustal movement rates in the modern period. Preferably, extended periods of from 50 to 100 years should be used. Gages and methods were rather poor in the last half of the 19th century, but were good enough for approximations of rates. Methods and equipment were quite satisfactory in the early part of the present century, but not up to the high standards of the present time.

6. Gages located in constricted areas are subject to errors in recording true lake level which in some cases it is not practical or desirable to eliminate. Few of these errors have any effect on determination of crustal movement rates. Instrument errors are generally negligible or compensatory, except for float lag and humidity effects, which can be minimized. Operator errors are very remote today, and past errors, if not detected at the time, are minimized in the monthly mean averages.

7. Wind set-up causes the largest error by far in determination of true lake level. Errors due to differences in barometric pressures are appreciable, but are compensating over long periods. The effect of wind set-up is most felt on Lakes Erie and Ontario, and is believed to be insignificant on the other lakes. Long period records tend to minimize meteorological effects. For short periods gage differences may represent wind set-up almost entirely, but for long periods relative crustal movement is evident

if it exists intact between the two gages. Meteorological effects have no bearing on determination of rates over long periods.

8. Precise levels are the only acceptable means for determining rates of movement where water level transfers cannot be made. The present and past systems of vertical control on the lakes are of high quality. Present day effects on water levels of shifts in bench marks and gage zeros are non-existent, and those of the past are unlikely to be perpetuated in the records. The 1948 rate at Oswego relative to sea level at New York is apparently in error, and will be replaced by means of a new computation from Father Point.

9. The Father Point gage is the most satisfactory on the Atlantic seaboard as a reference zero or IGLD from the standpoint of stability. It is believed to be slightly above sea level in the order of 0.2 foot. The eustatic rise in mean sea level is about 0.33 foot, but this quantity has no effect on relative rates of crustal movement.

## VII. RECOMMENDATIONS

1. Review the physical location of all gages to determine which are affected by meteorological conditions by being in constricted areas. Without necessarily changing the general location, move the gage to a point where it will record true lake level for the area.

2. Change all floats to 10 inch diameter floats, if well is 12 inches in diameter or larger and other conditions permit. When necessary to change a well or install a new one where a sump is impractical, use 12 inch pipe or larger.

3. Install on appropriate gages the standard Stevens time markers and reversal indicators to be used as base line markers for detection of changes in chart paper due to excessive humidity.

4. In preparation for the next revision of IGLD, take steps at once to obtain necessary meteorological factors to permit corrections for wind set-up and barometric pressure effects to be made in connection with the principal water level transfers on Lakes Erie and Ontario. Install dependable recording gages at the terminal points of principal level lines.

5. From instrumental differences between bench marks of early and recent precise level lines, determine rates of crustal movement along the route from Father Point to Kingston. Make check computations from New York via Rouses Point and via Oswego.

## VIII. REFERENCES


Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1961, Establishment of International Great Lakes Datum (1955), 18 pp.

Freeman, J. R., 1926, Regulation of the Great Lakes; Sanitary District of Chicago, 548 pp.

Greenman, E. F., and Stanley, G. M., 1940, A Geologically Dated Camp Site, Georgian Bay, Ontario; American Antiquity, Vol. 5, No. 3, pp. 194-199.

Gutenberg, Beno, 1941, Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior; Bull. Geol. Soc. America, Vol. 52, pp. 721-772.

____________________, 1942, Is the Land Around Hudson Bay at Present Rising? Am. Jour. Sci., Vol. 240, pp. 147-149.

Hough, J. L., 1958, Geology of the Great Lakes; Univ. of Ill. Press, Urbana, 313 pp.

____________________, 1963, The Prehistoric Great Lakes of North America; American Scientist, Vol. 51, No. 1, pp. 84-109.

Leverett, Frank and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the History of the Great Lakes; U. S. Geol. Survey Mon. 53, 529 pp.

MacLean, W. F., 1961, Postglacial Uplift in the Great Lakes Region; Great Lakes Research Div., Inst. of Sci. and Tech., Univ. of Mich., Ann Arbor, pp. 234.

____________________, 1962, Personal Communication, Nov. 21.

Moore, Sherman, 1948, Crustal Movement in the Great Lakes Area; Bull. Geol. Soc. America, Vol. 57, pp. 697-710.

Moseley, E. L., 1904, Formation of Sandusky Bay and Cedar Point; Proc. Ohio State Acad. of Sci., Vol. IV, Part 5, pp. 179-238.

Rossiter, J. R., 1962, Director, Permanent Service for Mean Sea Level, Birkenhead, Eng., Personal Communication, Oct. 31.

Stanley, G. M., 1935, Abrupt Decline of the Whittlesey Beach at Birmingham, Michigan; Papers Mich. Acad. of Sci., Arts and Letters, Vol. XXI, pp. 445-452.

Stevens, J. C., undated, Hydrographic Data Book, Sixth Edition; Leupold & Stevens Instruments, Inc., Portland, Ore., 118 pp.